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A COMPUTER AIDED METHOD FOR THE MEASUREMENT OF FIBER DIAMETERS BY LASER DIFFRACTION

by

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Thesis Advisor: Professor Edward M. Wu

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This thesis investigates the computer aided measurement of fiber diameters by laser diffraction. The proposed system consists of a light sensitive Random Access Memory (RAM) chip which collects light intensity data from the laser diffraction pattern. Measurements of the spatial location of the nodes of the diffraction pattern enables the calculation of the fiber diameter. These measurements may be performed manually which is tedious and requires subjective judgement of the nodes. The alternative method of direct processing of the intensity pattern was investigated. Simulation is conducted to examine the feasibility of this method. Results show such a system to be capable of providing one order of magnitude greater accuracy than optical microscopy measurements (with a shearing eyepiece) and double the accuracy of manual laser diffraction methods with the added advantage of permitting the option of total computer automation in data interpretation.

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A Computer Aided Method for the Measurement of Fiber Diameters by Laser Diffraction

by

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Submitted in partial fulfillment of the requirements for the degree of

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ABSTRACT

This thesis investigates the computer aided measurement of fiber diameters by laser diffraction. The proposed system consists of a light sensitive Random Access Memory (RAM) chip which collects light intensity data from the laser diffraction pattern. Measurements of the spatial location of the nodes of the diffraction pattern enables the calculation of the fiber diameter. These measurements may be performed manually which is tedious and requires subjective judgement of the nodes. The alternative method of direct processing of the intensity pattern was investigated. Simulation is conducted to examine the feasibility of this method. Results show such a system to be capable of providing one order of magnitude greater accuracy than optical microscopy measurements (with a shearing eyepiece) and double the accuracy of manual laser diffraction methods with the added advantage of permitting the option of total computer automation in data interpretation.

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LIST OF SYMBOLS

α	Argument of the Bessel Functions
a	Width of a slit in Fraunhofer diffraction theory
b_n	Bessel coefficient ($J_n/H_n^{(2)}$)
d	Diameter of a fiber
θ	Angular position in diffraction pattern (radians)
J_n	Bessel function of the first kind
$H_n^{(2)}$	Hankel function of the second kind
I_{TIR}	Threshold Intensity Ratio
K_o	Constant associated with the real fiber intensity equation
λ	Wavelengh of laser (632.8 nm for He-Ne)
L	Longitudinal position defining distance from fiber to diffraction pattern
m	Integer indicating interference node number
P	Geometric center of diffraction pattern
Δx	Width of Micron Eye array (approximately 4.4 mm)
x	Lateral position in diffraction pattern (perpendicular to laser beam)
Y_n	Bessel function of the second kind

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I. INTRODUCTION

Fiber reinforced composites are replacing structural metal components in today's aircraft. The high strength and reduced weight of composites results in less drag, increased payload, and longer fatigue life. Additionally, the directional properties of composite materials provide unique design advantages over conventional materials.

As with many developing technologies, the reasons for the success of fiber composites was not initially appreciated. Tsai [Ref. 1:p. 2] states that fortunately the modern composite was so strong it was reliable and competitive in spite of less than optimum design practice. Over the last twenty years, much progress has been made in understanding the micro and macro mechanics of composite materials. As this knowledge matures and is incorporated into the design process, the full potential of these materials can be realized.

An important contribution to the design process is modeling structural reliability. Development of probabilistic models for a composite must take into account the complex relationships that exist between fiber and matrix.

One important parameter in the probabilistic model is fiber diameter, since variations in fiber diameter affect fiber failure density. Therefore, more accurate fiber diameter measurement results in an enhanced reliability model and a more quantitative prediction of structural reliability.

The purpose of this research is to investigate a computer aided method of fiber diameter measurement. The existing procedure of diameter measurement by laser diffraction is accurate to within 0.5% [Ref. 2:p. 210]. It is desired to improve this accuracy by interpreting the diffraction pattern with a light sensitive RAM chip.

The presentation begins with a discussion of diffraction pattern analysis. This is followed by an introduction to the Micron Eye's theory and operation. Next, the simulation is discussed in depth followed by the results and conclusions.

II. BACKGROUND

Fiber diameter measurement by laser diffraction is conducted by obstructing a collimated laser beam with a fiber sample. A diffraction pattern results and is characterized by alternating maxima and minima symmetric about a central maximum. (See Figure 1)

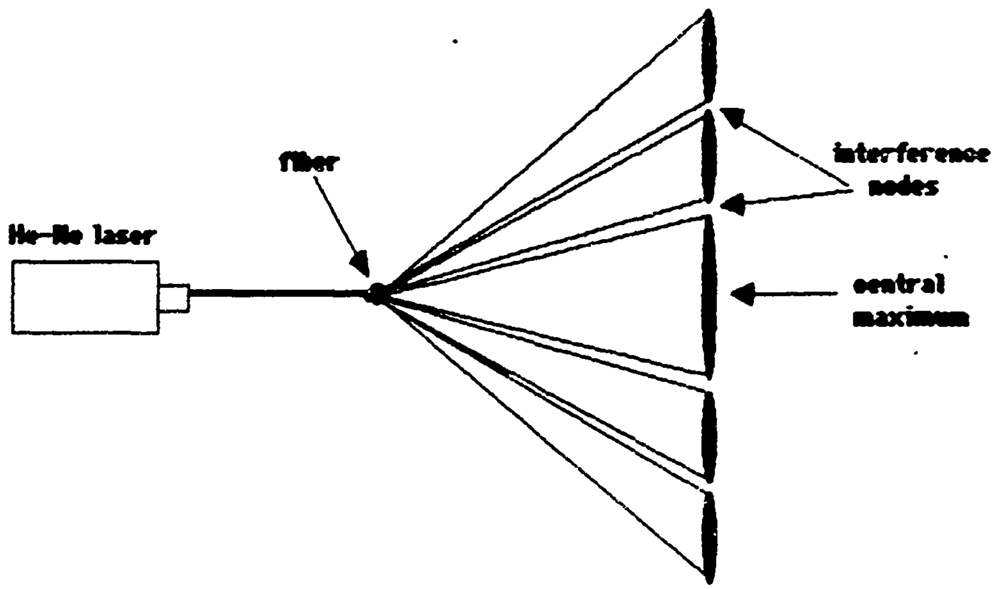


Figure 1. Fiber Diameter Measurement by Laser Diffraction

In previous work, Perry, Ineichen, and Eliasson, [Ref. 3] and Bennett, [Ref. 4], interpretation of the diffraction pattern consisted of finding the distance between interference nodes (minima). This distance is related to the fiber diameter.

Bennett used the slit approximation (Appendix A) to relate the distance between nodes to the fiber diameter. Perry, et al., introduced a more exact solution by Kerker, [Ref 5:p. 260] and compared it to the slit approximation. Perry, et al., concluded that the slit approximation should be treated with caution. Therefore, Kerker's solution has been adopted for this study.

In his paper, Bennett successfully demonstrated the feasibility of using the light sensitive RAM chip for diameter measurements [Ref 4]. An IS32 OPTICRAM MICRON EYE, manufactured by Micron Technology, Inc., was connected as a peripheral device to an Apple II+ computer. By positioning the Micron Eye so that two interference nodes fit on its surface (see Figure 2), an "exposure" of the diffraction pattern could be printed by the computer (see Figure 3). Analysis of the printed diffraction pattern gave the diameter of the fiber using the slit approximation of Fraunhofer diffraction theory (see Appendix A).

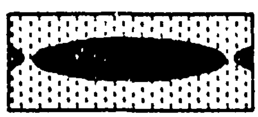


Figure 2. Micron Eye Array with Two Interference Nodes

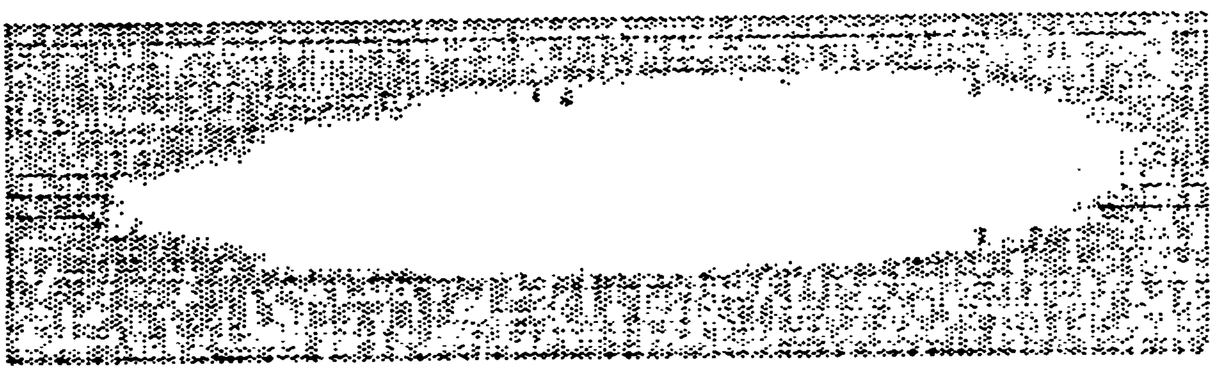


Figure 3. Typical Micron Eye Photograph of Interference Nodes

III. DIFFRACTION PATTERN ANALYSIS

Measuring fiber diameters by laser diffraction, requires an understanding of the diffraction pattern. This chapter introduces some features of diffraction patterns which will be useful in later analysis.

A. FUNCTIONAL DESCRIPTION OF THE DIFFRACTION PATTERN

The diffraction pattern of a fiber can be described as follows:

$$I/I_o = (2/K_o L\pi) \left| b_o + 2 \sum b_n \cos(n\theta) \right|^2 \qquad (1)$$

where θ = the scattering angle

$K_o = 2\pi / \lambda$ (λ = laser wavelength)

$b_n = J_n(\alpha) / H_n^{(2)}(\alpha)$

and $\alpha = \pi d_f / \lambda$ (d_f = fiber diameter)

$J_n(\alpha)$ are Bessel functions of the first kind,

$H_n^{(2)}(\alpha)$ are Hankel functions of the second kind.

A formal introduction of equation (1) and the related Fraunhofer diffraction theory is presented in Appendix A.

Figure 4 depicts the three dimensional nature of the diffraction pattern. Equation (1) describes the intensities along one linear position, or slice, of the three dimension pattern.

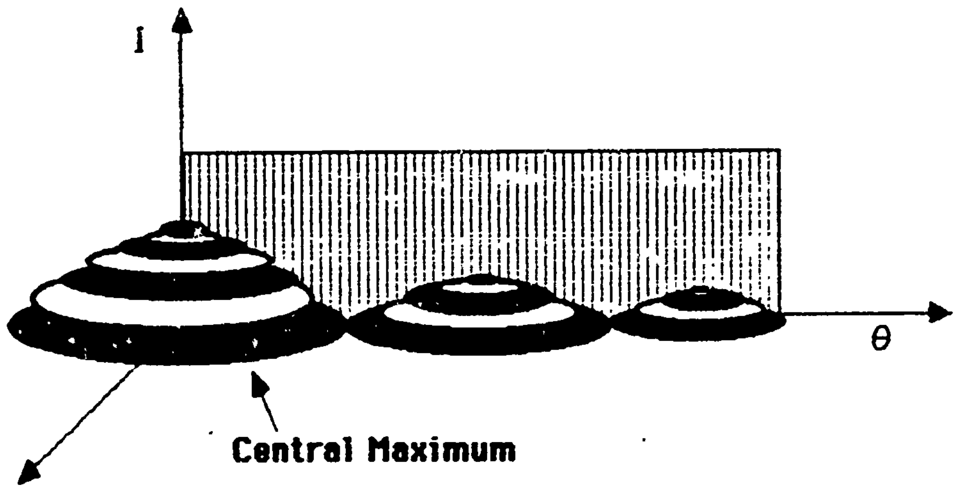


Figure 4. Three Dimensional Diffraction Pattern

A plot of equation (1) is the Intensity Profile which shows the Intensity Ratio (I/I_o) versus the angle theta, for a given fiber diameter and a given fiber to screen distance L. Figure 5 shows a typical Intensity Profile for a fiber diameter of 6.5 microns.

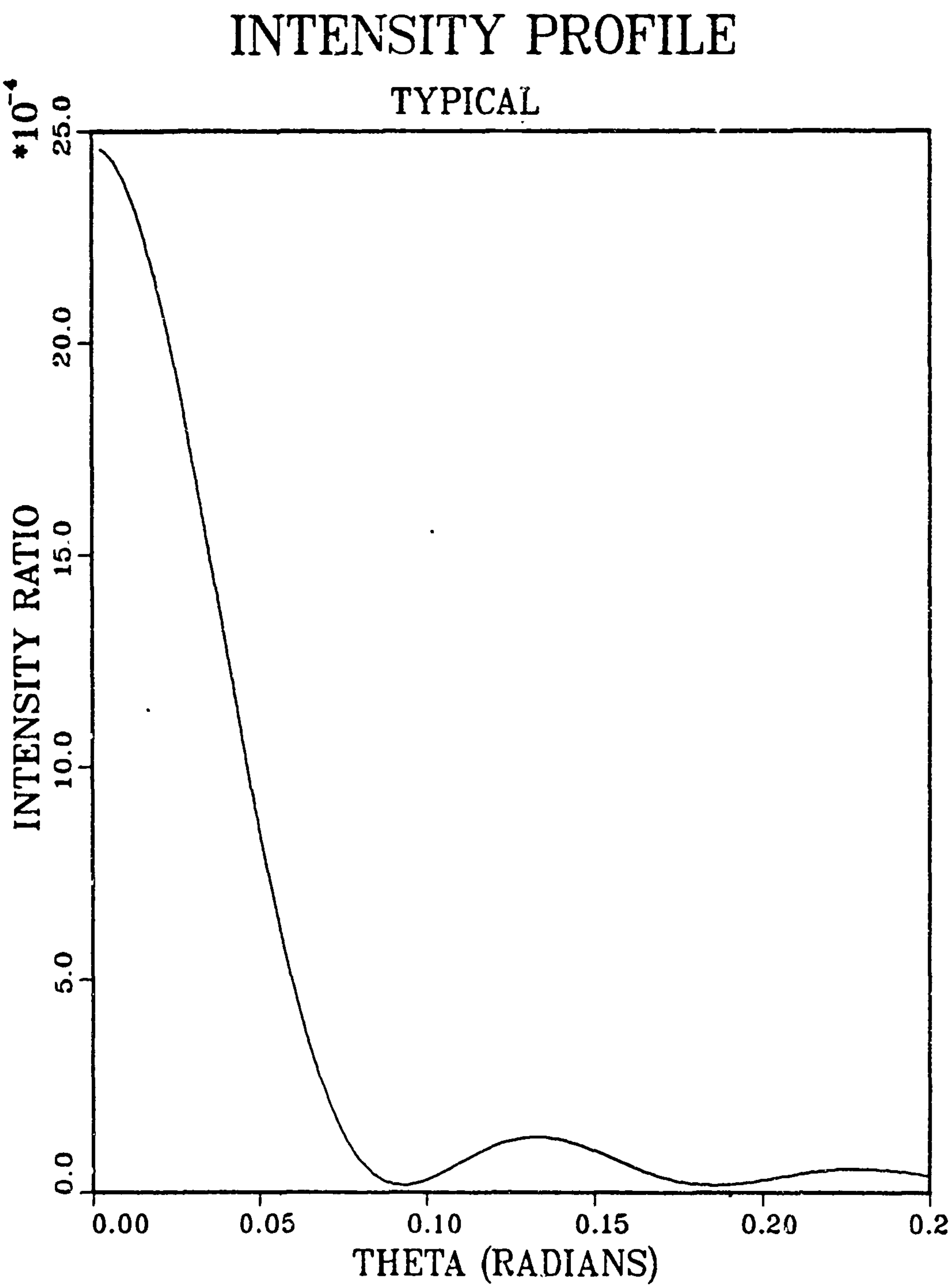


Figure 5. Typical Intensity Profile

B. FEATURES OF THE INTENSITY PROFILE CURVES

The intensity profile has several features worth noting. The first is the central (or zeroth order) maximum. The central maximum is the largest peak in Figure 5 and it is many times more intense than the subsequent maxima. It should also be obvious that the profile is symmetric about the central maximum.

Other features of the curves are shown in Figure 6. Figure 6 is an enlarged view of one of the higher order maxima and associated minima. As discussed in Appendix A, the higher order maxima are not centrally located between the minima, rather they are displaced slightly towards the central maximum. Therefore, the higher order peaks are asymmetric about their maxima. This asymmetry means the maximum derivative on the upslope side of the curve will be greater than the maximum derivative on the downslope side of the curve. This difference is dealt with later when tuning for the optimum exposure is discussed.

The minima in Figure 6 are also distinctive features of the curves. In Appendix A, it is shown that the location of the minima are explicitly related to the diameter of the fiber using the slit approximation:

m = # of interference node

$$\theta_{min} = \sin [m\lambda/d] \qquad (2)$$

λ = laser wavelength

d = diameter of fiber

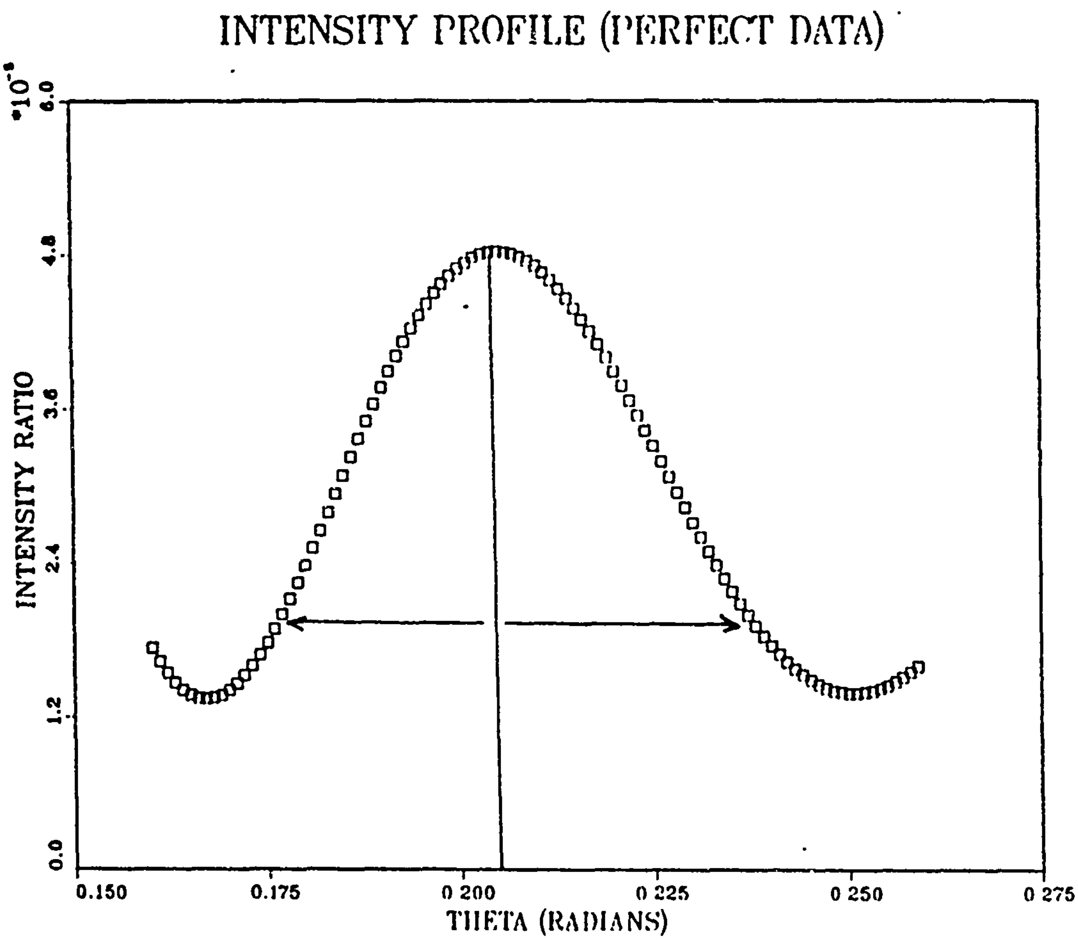


Figure 6. Features of the Intensity Profile Curve

Equation (2) is only an approximation for a fiber, but it is useful for preliminary analysis. Such analysis includes:

(1) determining where to place the Micron Eye for data collection and,

(2) providing and initial guess of fiber diameter from diffraction pattern data.

C. EFFECT OF DIAMETER ON THE INTENSITY PROFILE CURVES

Figure 7 shows the effect of diameter on the Intensity Profiles. Note that successive maxima and minima are further from the central maximum for fibers of smaller diameter. This behavior will be important to later analysis.

D. THE MAXIMUM DERIVATIVE AND THE MINIMUM NUMBER OF POINTS

The goal of automated fiber diameter measurement is to find the diameter rapidly and accurately. Speed and accuracy can be exclusive. One can imagine that collecting all the points on the Intensity Profile curve will result in an almost exact determination of fiber diameter, at the expense of time. Two questions must be answered. First, what is the minimum number of points to uniquely describe an intensity profile? Second, where on the curve should these points be obtained?

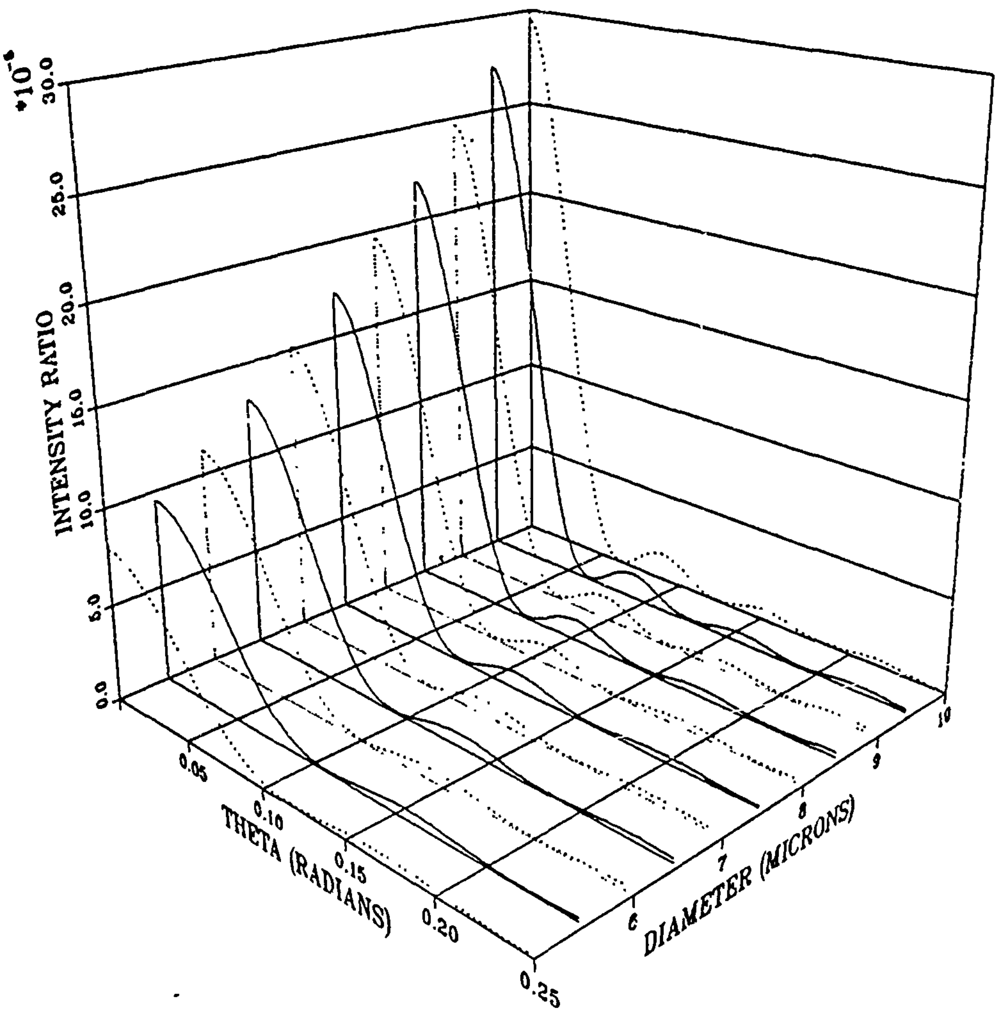


Figure 7. Effect of Diameter on Intensity Profiles (3-D)

1. Minimum Number of Points

Equation (1) consists of an infinite series. Determining the minimum number of points to uniquely define an infinite series is not a straightforward procedure. Cursory inspection of Figure 8 leads to the conclusion that one point will not uniquely define the curve, since intensity curves for many diameters pass through the same point (e.g., at $\theta = .04$ radians). If the absolute intensity is not known, 2 points will not provide a unique solution either. For the case of non-absolute intensity measurements (as is the case in this experimental set-up) 3 points appears to uniquely define a curve.

The curve in Figure 9 illustrates this observation. An imaginary line is fixed through three points (i.e., the experimental measurements). The absolute intensities of these three points are not known, and neither are the absolute spatial locations with respect to the central maximum (i.e., θ). Only the relative spatial locations among these points are known. Iteration of the diameter is equivalent to moving this line (with the x marks fixed relative to each other) along different locations on the curve, trying to match all three points. This iteration can be repeated on curves of different diameters (Figures 10 and 11) and no other match can be found. Thus, this argument defines three points as the minimum required to uniquely determine the intensity profile curve.

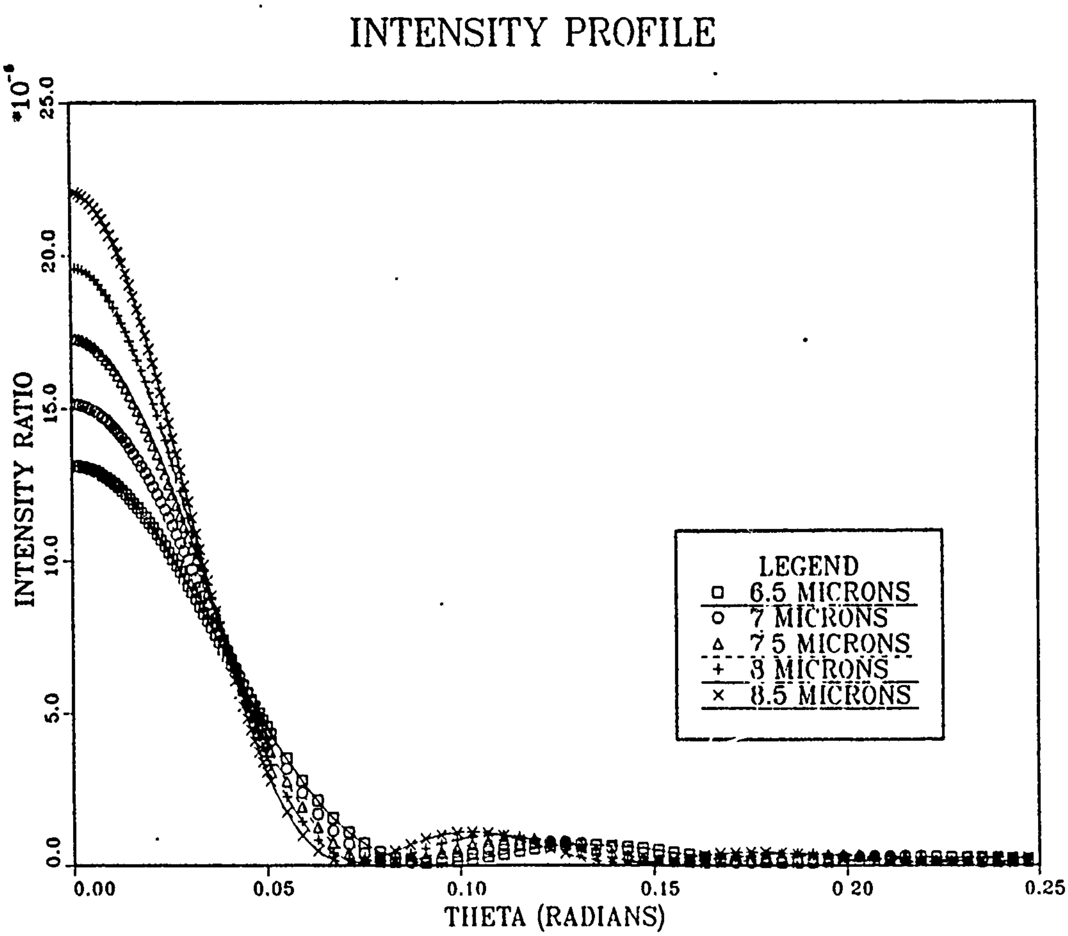
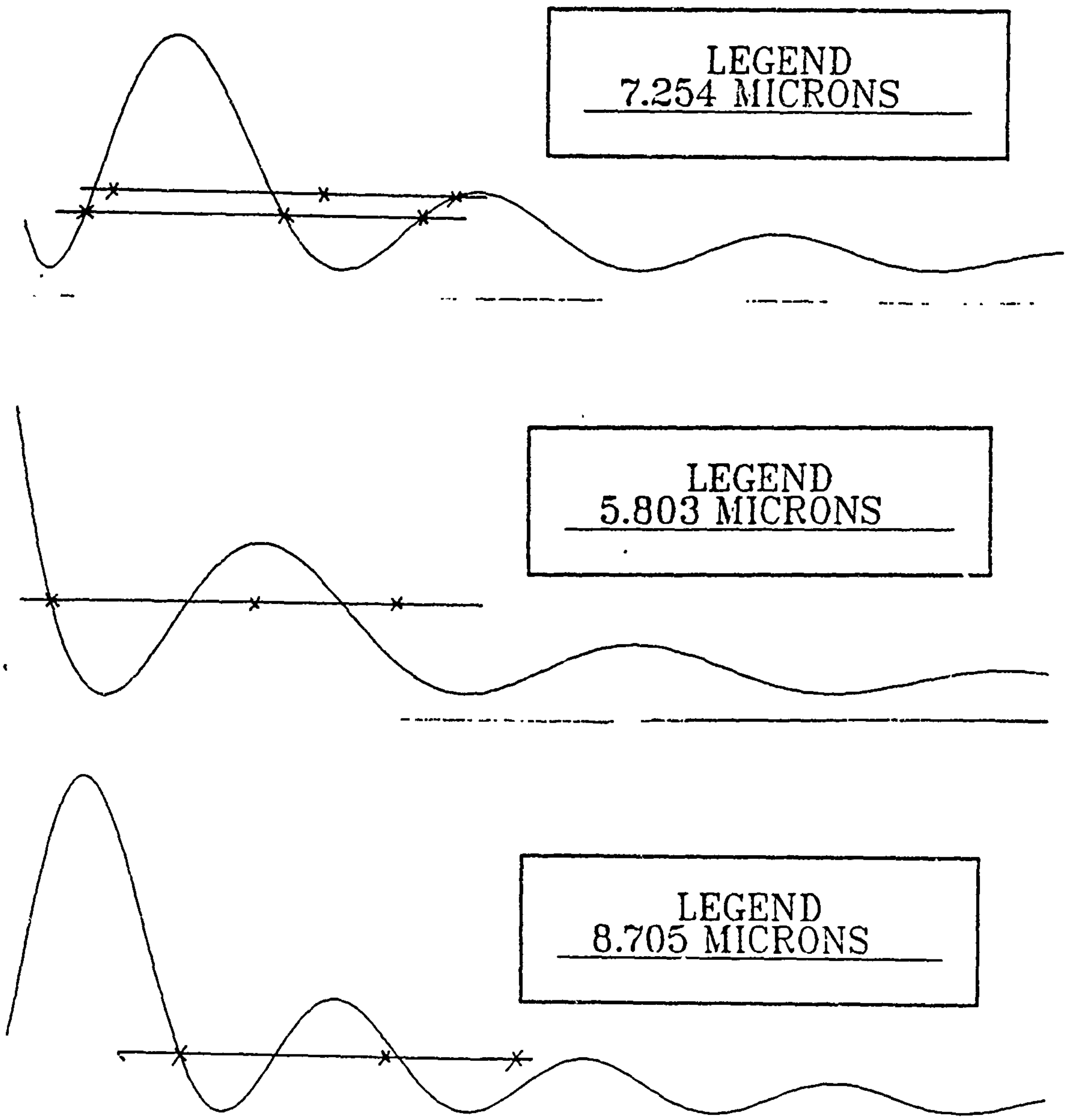


Figure 8. Effect of Diameter on Intensity Profiles (2-D)



Figures 9, 10, 11. Three Points to Define a Curve

2. Maximum derivative

Having heuristically established that three points are required, the next step is to determine the optimum location from which to select the points. For example, if points are selected at the mimima (or maxima) a wide variation in theta results from a small change in Intensity Ratio. This variation is defined by the derivative of the Intensity Ratio with respect to Theta, and at the extrema this derivative is very small. It can be shown that the points on the curve where the derivative is a maximum will have the least variation error. Therefore, it is desirable to use the Intensity Ratios corresponding to the maximum derivatives as the optimum intensity ratios for the three points. These Intensity Ratios will be referred to as the Threshold Intensity Ratios.

Figure 12 shows a portion of an Intensity Profile with a derivative curve (absolute value) superimposed. Vertical lines drawn through the derivative curve maxima intersect the Intensity Profile showing the location of the optimum (threshold) intensity points.

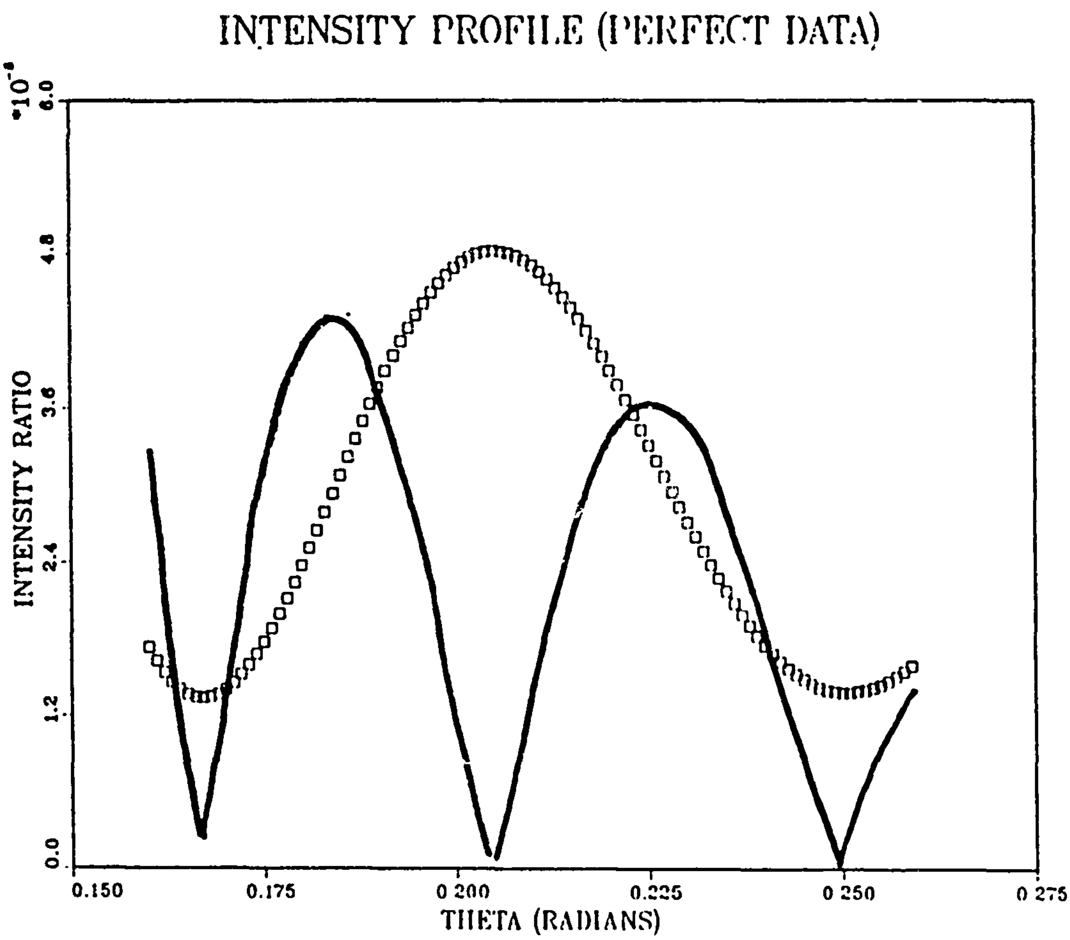


Figure 12. Intensity Profile with Superimposed Derivative Curve

IV. MICRON EYE

The MICRON EYE image sensor is an optically sensitive Random Access Memory (RAM) chip capable of sensing an image and translating it to digital computer compatible signals. The Micron Eye was selected to introduce automation to the existing techniques of fiber diameter measurement by laser diffraction. Automation is expected to increase the speed and accuracy of diameter measurements. This chapter introduces the theory and operation of the Micron Eye.

A. PHYSICAL LAYOUT AND DIMENSIONS

The Micron Eye (IS32 OpticRAM ™) has two arrays each containing 128 rows x 256 columns of sensors. This application will use only one of the arrays. The size of an array is 4420 μm by 877μm. (See Figure 13)

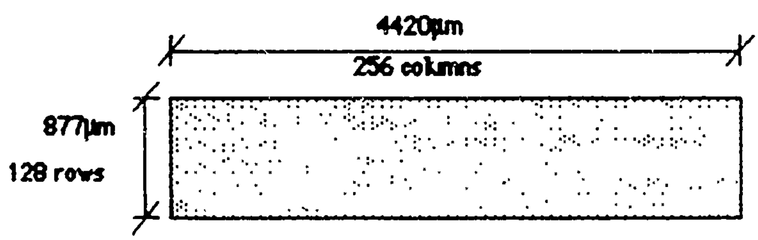


Figure 13. Micron Eye Array

Each sensor is a light sensitive element is called a pixel. The physical organization of the pixels is shown in Figure 14. The 128 x 256 elements actually map into a 129 x 514 "cell placement grid". This arrangement leaves "space pixels" in between each pixel in the row direction. The space pixels can be set high, low, or to the level which agrees with the majority of its nearest neighbors.

B. THEORY OF OPERATION

The pixels are capacitors which discharge a preapplied voltage at a rate proportional to both the intensity and duration of the impinging light. The voltage in an exposed capacitor is read and digitally compared to the fixed threshold voltage. If the voltage is below threshold the pixel is read as WHITE. If the voltage is above threshold the pixel is read as BLACK. The digital comparison concept will be an important part of the simulation in the next chapter.

After a pixel is read, the row containing that pixel is refreshed. Refreshing sets all pixels which are below threshold to 0 volts, and all pixels which are above threshold to +5 volts. [Ref. 6]

IS32 OpticRAM™ TOPOLOGICAL INFORMATION

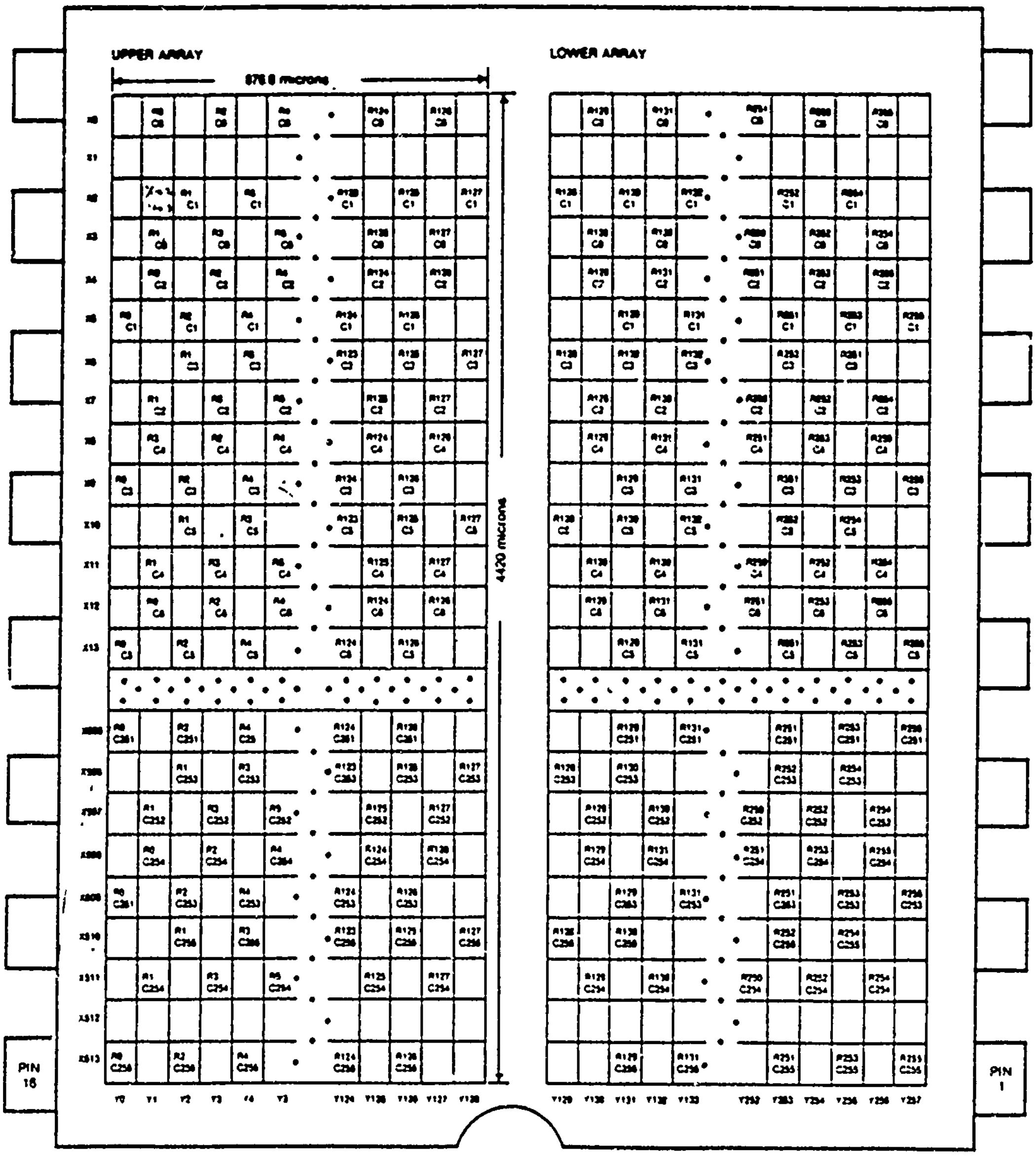


Figure 14. Micron Eye Physical Organization

1. Operation of the Micron Eye

Operation of the Micron Eye is simple. The current research configuration uses an Apple Macintosh (512K) computer. Control software is provided by Micron Technology, Inc. The Micron Eye is connected through either the modem or printer port. (See Figure 15) The computer also acts as the power source for the Micron Eye.

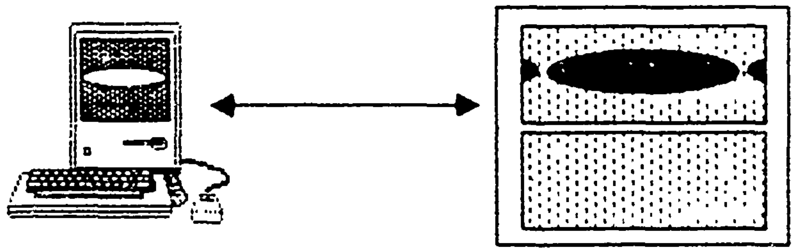


Figure 15. Macintosh and Micron Eye

2. Exposure

An exposure of a portion of the diffraction pattern can be made by varying exposure times. A sample exposure is shown in Figure 16. It is important to visualize that this exposure represents a cross section of the intensity profile curve.

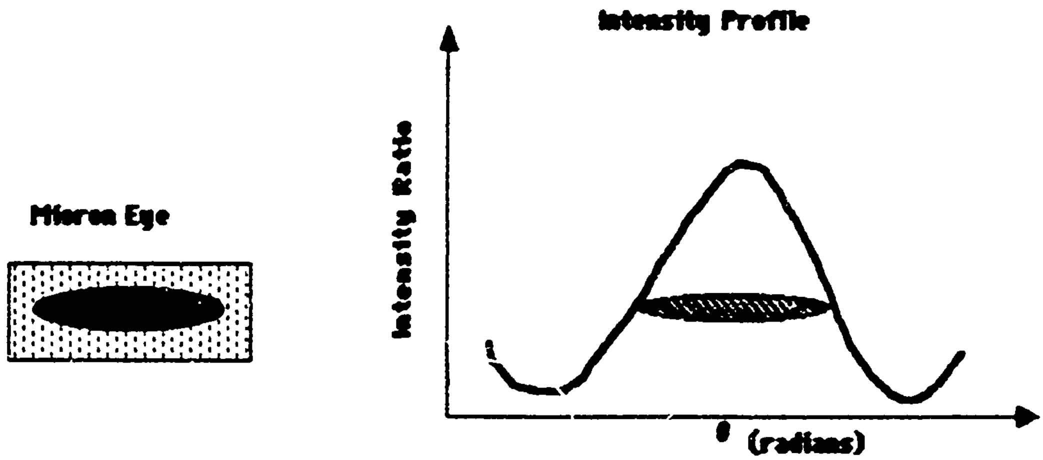


Figure 16. Exposure and Its Relation to Intensity Profile

Longer and shorter exposure times will vary the size of the cross section. Varying exposure time is equivalent to moving up or down the intensity ratio axis of the intensity profile curve.

C. INTENSITY MEASUREMENTS WITH THE MICRON EYE

Bennett [Ref. 4] used the Micron Eye to measure the distance between interference nodes. This approach was compatible with the slit approximation requiring only the theta locations of the interference nodes to give the diameter. In Kerker's equation [Ref. 5:p. 260], one cannot solve explicitly for **d**. The solution requires knowledge of the Intensity Ratios and their respective theta locations. For the Micron Eye, Intensity Ratios correspond to the user controlled exposure time.

1. <u>Two Approaches to Intensity Calibration</u>

The Micron Eye must be calibrated to a reference intensity level. One method to accomplish this would require two exposures. One at $I_1 + \Delta$ and another at $I_2 + \Delta$. Delta represents an unknown level above the zero (or absolute) intensity. (See Figure 17) The difference between these two values eliminates delta.

A second method requires a fiber of known diameter. One exposure of this "calibration" fiber will allow determination of the absolute intensity.

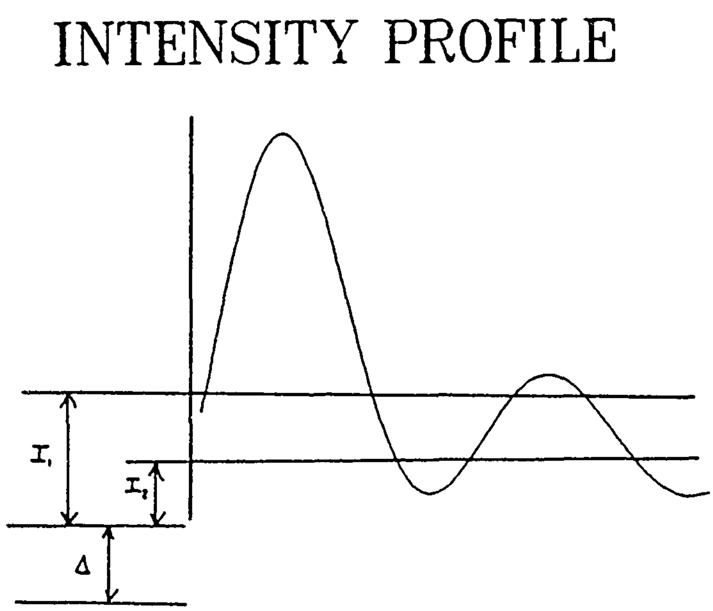


Figure 17. Calibrating the Micron Eye

V. SIMULATION

This chapter introduces the simulation of the Micron Eye / Laser Diffraction diameter measurement system. The simulation answers many questions relating to the real system:

(1) where should the Micron Eye be placed?
(2) what exposure is best?
(3) what accuracy can be expected?
(4) is the computer code valid?

The simulation combines diffraction pattern analysis with Micron Eye operation. The worth of the results will depend on the accuracy of the simulation.

A. COMPUTER PROGRAMS

Several computer programs have been written to conduct this simulation. These are:

(1) DATAMAKR
(2) EXPOSURE
(3) DIAFIND

Appendix B discusses these programs in detail.

Briefly:

(1) DATAMAKR is used to produce Intensity Ratio versus Theta data for a given fiber diameter **d**, and screen to fiber distance **L**. The user controls the number of points produce and their spacing.

(2) EXPOSURE reads the Intensity Profile data generated by DATAMAKR and recommends the optimum exposure based on the average of the intensity ratios corresponding to the maximum derivatives. Exposure will also introduce random error into the data, as desired.

(3) DIAFIND uses the data generated by EXPOSURE to find the diameter of the fiber. The programs begins with a user input guess of the diameter and conducts an iterative search / comparison routine to find the actual diameter of the data.

B. OVERVIEW

The general approach in examining the proposed system will be to consider a typical carbon fiber. This fiber has been assigned the arbitrary diameter of 7.254µm. Two additional fibers ±20% of the 7.254µm fiber are also considered. These fibers define the range of diameters from 5.803µm to 8.705µm. See Figures 18, 19, and 20 for Intensity Profiles curves for these diameters.

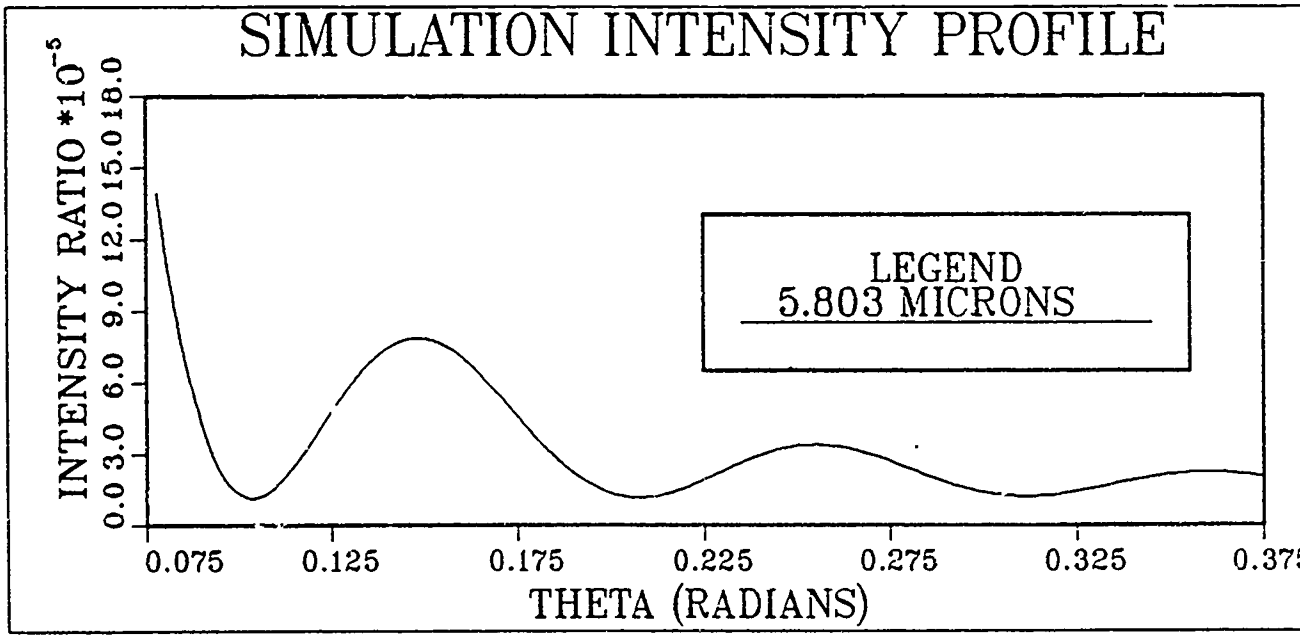


Figure 18. Simulation Intensity Profile (5.803μm)

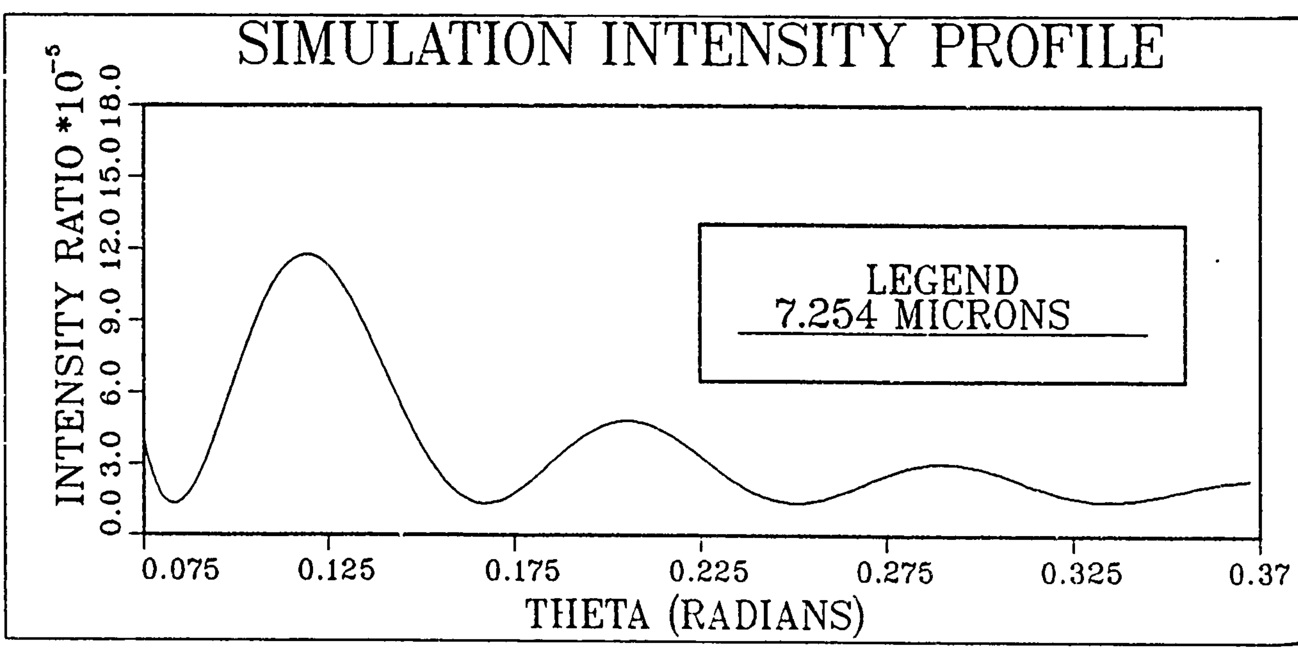


Figure 19. Simulation Intensity Profile (7.254μm)

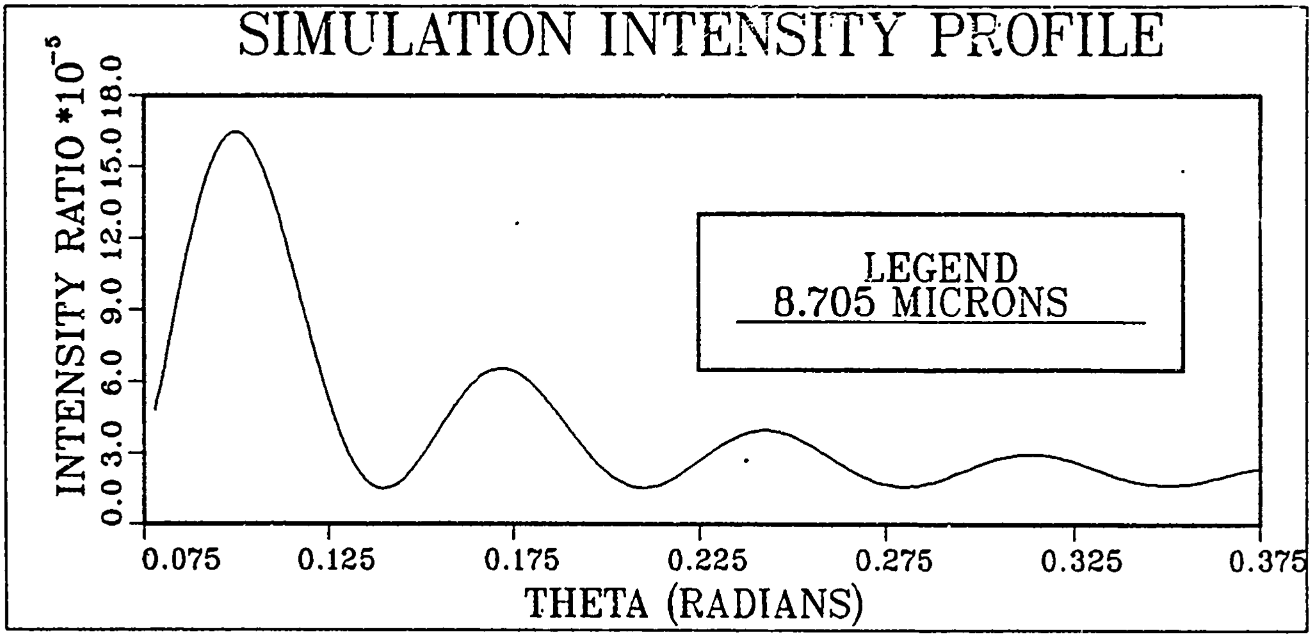


Figure 20. Simulation Intensity Profile (8.705μm)

C. POSITIONING OF THE MICRON EYE

In order to measure the diameter of the typical fiber, a method of postitioning the Micron Eye must be defined. Further, from this same position, it is desired to also measure the ±20% fibers. This requires that one position of the Eye permit fiber diameter measurements over the specified range of fiber diameters.

Such a position is defined such that three data points will be obtained for any fiber in the diameter range, as in Figure 21. First, a simpler case will be discussed to introduce positioning for a given diameter fiber.

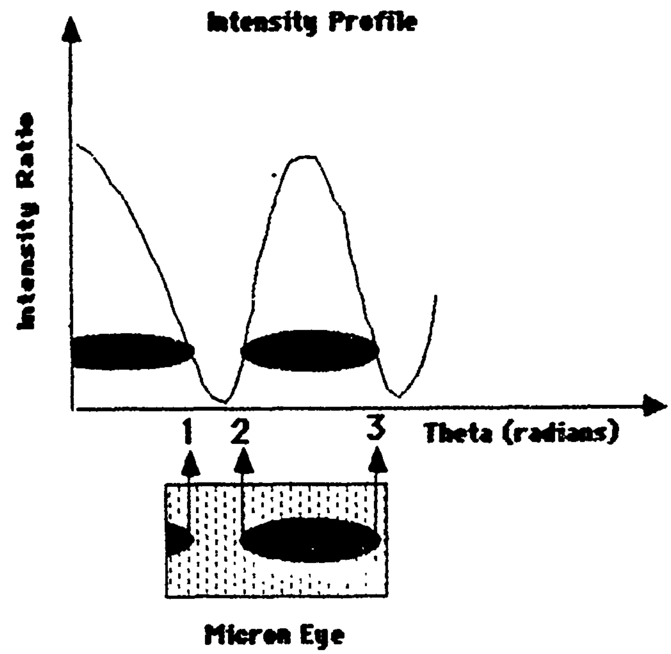


Figure 21. Exposure for Three Data Points

1. Positioning for a Single Fiber

Suppose an exposure of the first through the second interference nodes (2^{nd} maximum) was desired for the 7.254μm fiber. Figure 22 shows the relationship between the fiber and the Micron Eye:

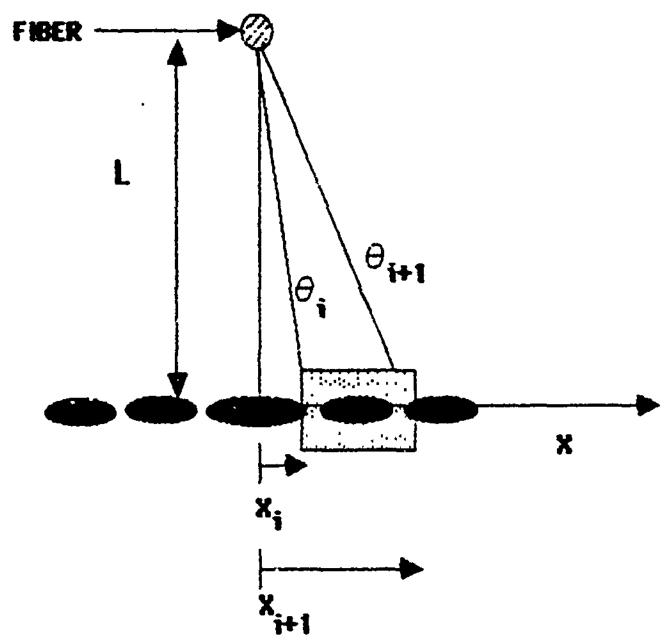


Figure 22. Micron Eye Placement in Diffraction Pattern

$$\theta_i = \tan^{-1} [x_i / L] \quad (3)$$

$$\theta_{i+1} = \tan^{-1} [x_{i+1} / L] \quad (4)$$

or $\tan \theta_{i+1} - \tan \theta_i = 1/L\,(x_{i+1} - x_i) = \Delta x/L$ (5)

take $\Delta x = 4.4$ mm (width of Micron Eye array)

With Δx fixed, one can adjust L so that any desired $\theta_{i+1} - \theta_i$ will fit on the Micron Eye's array. Recall that $\theta_{min} = \sin [\, m\lambda / d \,]$ equation (2), which will give the theta locations of the first and second interference nodes.

$\theta_{min} = \sin (m\lambda/d)$ where m = node #

λ = laser wavelength (632.8nm)

d = fiber diameter

for 7.254µm: θ_i = .08712 radians

θ_{i+1} = .17459 radians (for i = 1)

with θ_i and θ_{i+1} fixed, L is defined from equation (5):

$$L = \Delta x \,/\, [\tan \theta_{i+1} - \tan \theta_i] = 49 \text{ mm}$$

L is the distance of the Micron Eye from the fiber in the longitudinal direction. Referring back to equation (3), the lateral placement of the Eye is given (see Figure 23):

$$x_{inner} = L \tan(\theta) = 4.27 \text{ mm}$$

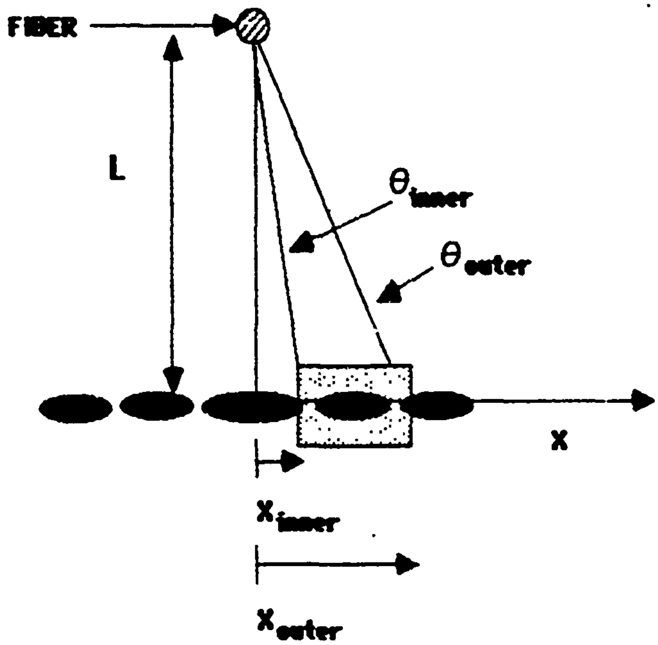


Figure 23. Micron Eye Position

Thus, equations (3) through (5) give the Micron Eye position for any desired **d**, θ_{i+1}, θ_i, L and **m**.

This position is not yet optimum for single diameter case. This analysis has captured only two interference nodes and the intervening maximum. Any exposure will yield information somewhere between the two extremes shown in Figure 24. The Micron Eye images correspond to the shaded areas of the intensity profile curve on the right side of Figure 24.

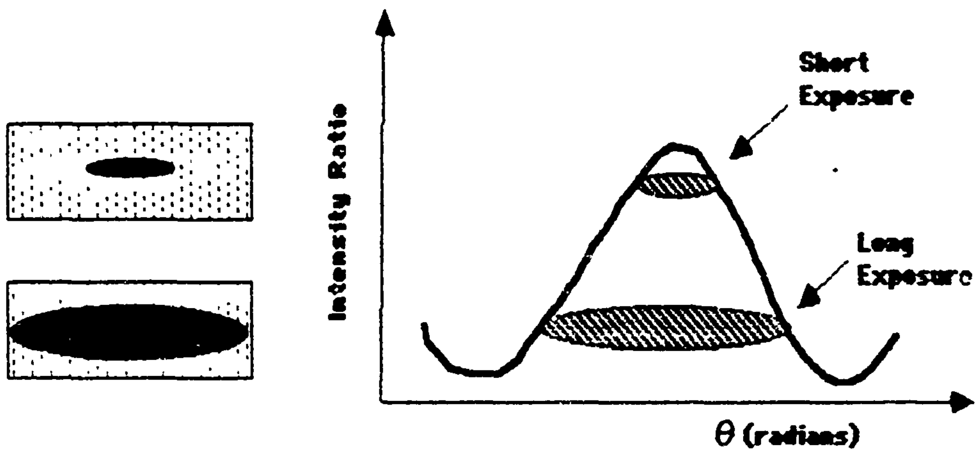


Figure 24. Short and Long Exposures

One method of finding the points would be to search the Micron Eye array data for a major axis. The endpoints of this major axis are the points required for the analysis. (See Figure 25)

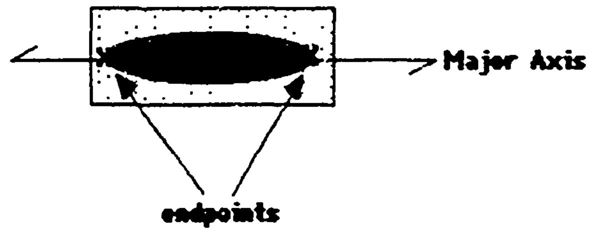


Figure 25. Endpoints of Major Axis

Recall from diffraction analysis (Chapter 3) that three points are required to define the intensity profile curve. Therefore, more of the diffraction pattern must be seen by the Micron Eye. A reduction in **L** will yield the third point. (See Figure 26) **L** should not be reduced any more than is necessary, since fewer pixels are being used to describe the data, degrading the resolution of the Micron Eye.

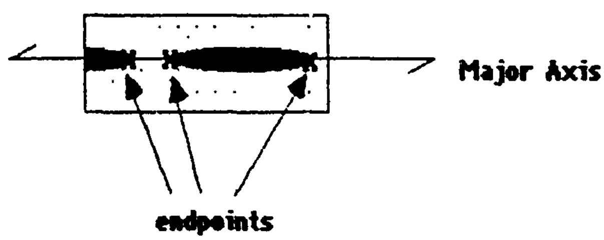


Figure 26. Three Points on Major Axis

2. Positioning the Micron Eye for a Range of Diameters

Consider the positioning of the Micron Eye so that three data points can be collected for a range of diameters. A "window" for the array must be defined which will ensure three points of data for any diameter in the specified range.

Examine the Relative Intensity Profile plot in Figure 27. θ begins at .075 radians which excludes the the central maximum. The central maximum is so intense, the Micron Eye's fastest exposure cannnot prevent overexposure. Therefore, the central maximum is not considered as a location for the window.

The window should also be located in a region where the maximum intensity corresponding the the largest diameter fiber is close to the maximum intensity of the smallest diameter fiber. This ensures the Threshold Intensity Ratio will be more representative for all diameter in the range. This condition occurs at the higher order nodes (2 or greater), as illustrated in Figure 28. The plot of intensity ratio derivatives also shows this condition in Figure 29.

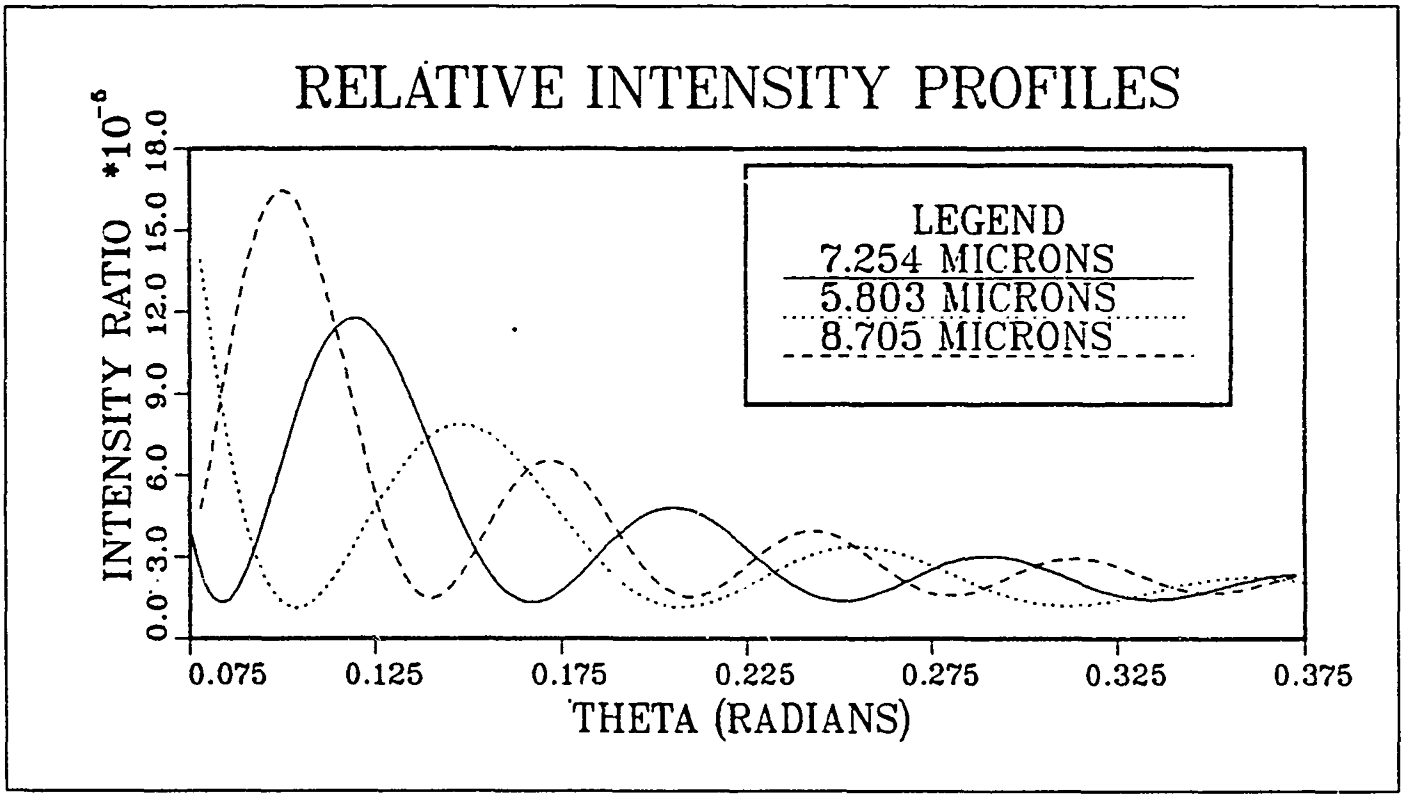


Figure 27. Relative Intensity Profiles

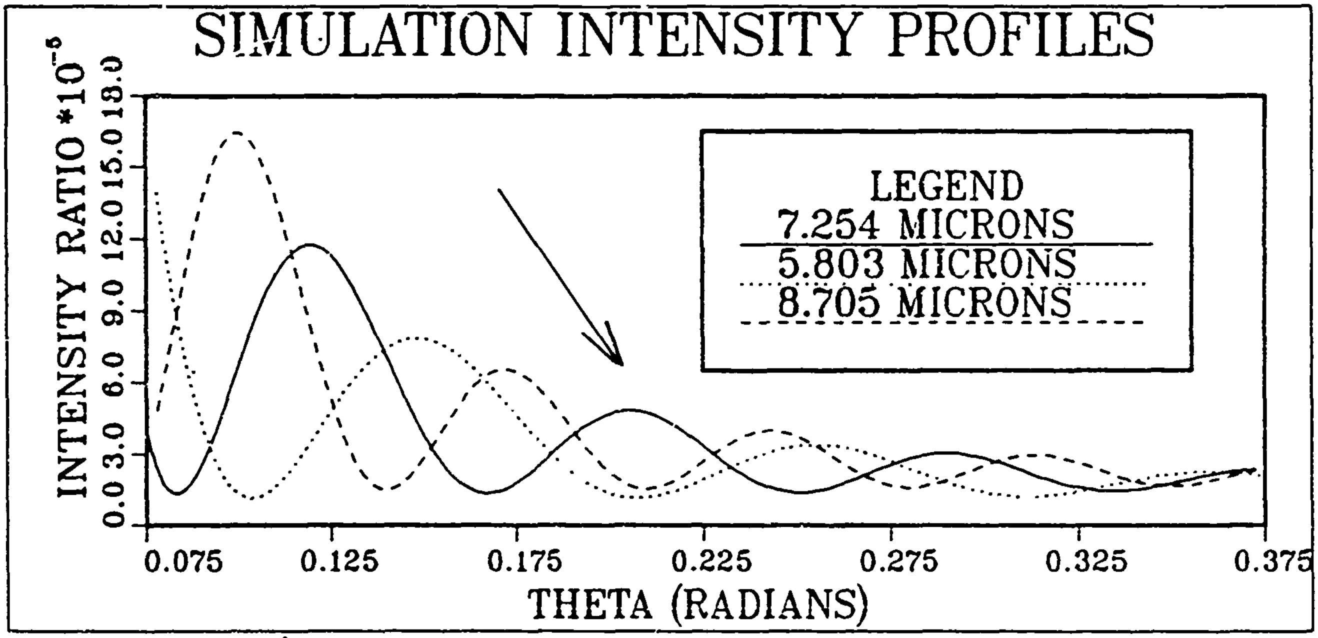


Figure 28. Region of Similar Maximum Intensities

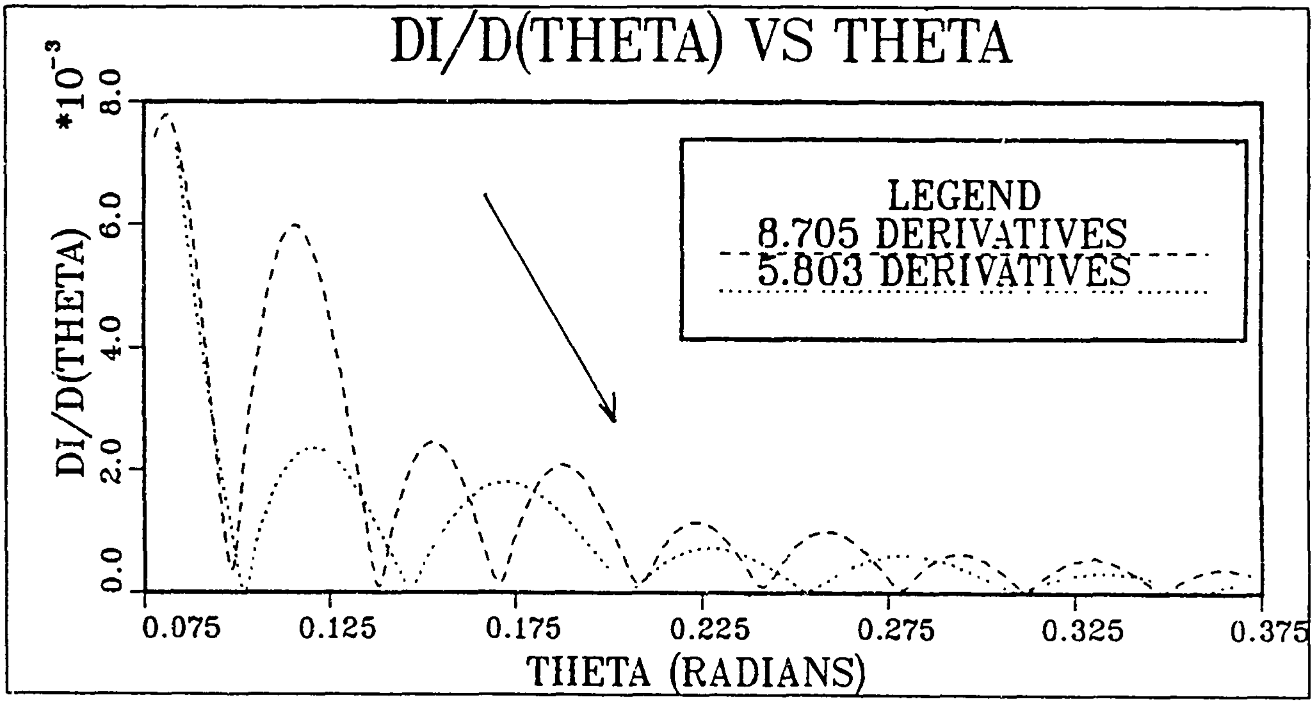


Figure 29. Region of Similar Intensity Ratio Derivatives

To obtain three points, at about 1.5 maxima are required. Since the distance between nodes is the greatest for the smallest diameter, find the θ locations for the smallest diameter which gives 1.5 maxima.

for 5.803μm:

$$\theta_{min2} = \sin(21/5.803\mu m) = .216 \text{ rads}$$

$$\theta_{min3} = \sin(31/5.803\mu m) = .321 \text{ rads}$$

Half of this range is about .050 radians and 1.5 maxima can be approximated by .165 -----> .321 radians. Admittedly, this is not a sophisticated method. The method is somewhat liberal and it was later discovered that a range of .165 to .300 radians was better than the larger range. This is because the minima are not of interest so the right hand minimum at .321 radians was discarded, and the range reduced to .300 radians. Only the part of the curve where the slope is a maximum needs to be "seen" by the array.

A quick check can be made to insure that the curve representing the maximum diameter in the range fits inside the window.

for 8.705μm:

$$\theta_{min2} = \sin(2 1 / 8.705) = .150 \text{ rads}$$

$$\theta_{min3} = \sin(3 1 / 8.705) = .216 \text{ rads}$$

$$\theta_{min4} = \sin(4 1 / 8.705) = .286 \text{ rads}$$

The next step is to determine the distance L at which the Micron Eye will cover the θ range of .165 ---> .300 radians. Equation (5) defines the longitudinal position and equation (3) defines the corresponding lateral position:

$$L = \Delta x / [\tan(\theta_{i+1}) - \tan(\theta_i)] = 30 \text{ mm}$$

$$x_i = L \tan(\theta_i) \approx 5 \text{ mm} \qquad \text{(inboard position of array)}$$

VI. SIMULATION: THE PERFECT AND IMPERFECT DATA SETS

Now that a window has been defined (θ range) for the diameter range, it is necessary to construct perfect data for the simulation diameters: $\mathbf{d}_1$, $\mathbf{d}_2$, and $\mathbf{d}_3$. DATAMAKR generates this data for a given $\mathbf{d}$ and L, over the specified range of θ. Additionally, the number of points over the specified range must be chosen. The number of points defines the θ interval and corresponds to the physical spacing of the pixels in the Micron Eye array which is on the order of 10μm. To match this spacing, 400 points were generated over the interval .165 to .300 radians.

A. DIGITIZATION OF DATA

The EXPOSURE program is used to digitize the perfect data. Digitizing the data is the simulative analog of the Micron Eye threshold voltage comparison. In the simulation, any intensity ratios above a certain ratio (call it the *threshold ratio*) are assigned a value of 1 and any intensity ratio below the threshold ratio are assigned a value of 0.

1. Determining the Threshold Intensity Ratio

Before EXPOSURE can digitize the perfect data, the threshold ratio must be determined. EXPOSURE calls the subroutine DERIV which calculates the derivatives of the intensity profile data at each theta location.

DERIV proceeds to search for all the local maximum derivatives. The average of the maximum derivatives is returned to the EXPOSURE program and is used as the threshold intensity.

After the data is digitized with respect to the threshold intensity, the digital data is searched to find the theta locations where the intensity changes from 0 --> 1 or 1 --> 0. The values for theta at these locations are averaged and this average is taken to be the theta location where the threshold intensity is located. The averaging of theta is based on the fact the Intensity Profile curve is approximately linear in the region of the Threshold Intensity Ratio. Figure 30 shows the general location of the Threshold Intensity Ratio.

In the simulation, EXPOSURE finds three average theta locations corresponding to the threshold intensity ratio. These data are stored in a data file which is subsequently input to the program DIAFIND. DIAFIND prompts the user to input an initial guess of the diameter and proceeds to find the diameter associated with the EXPOSURE data.

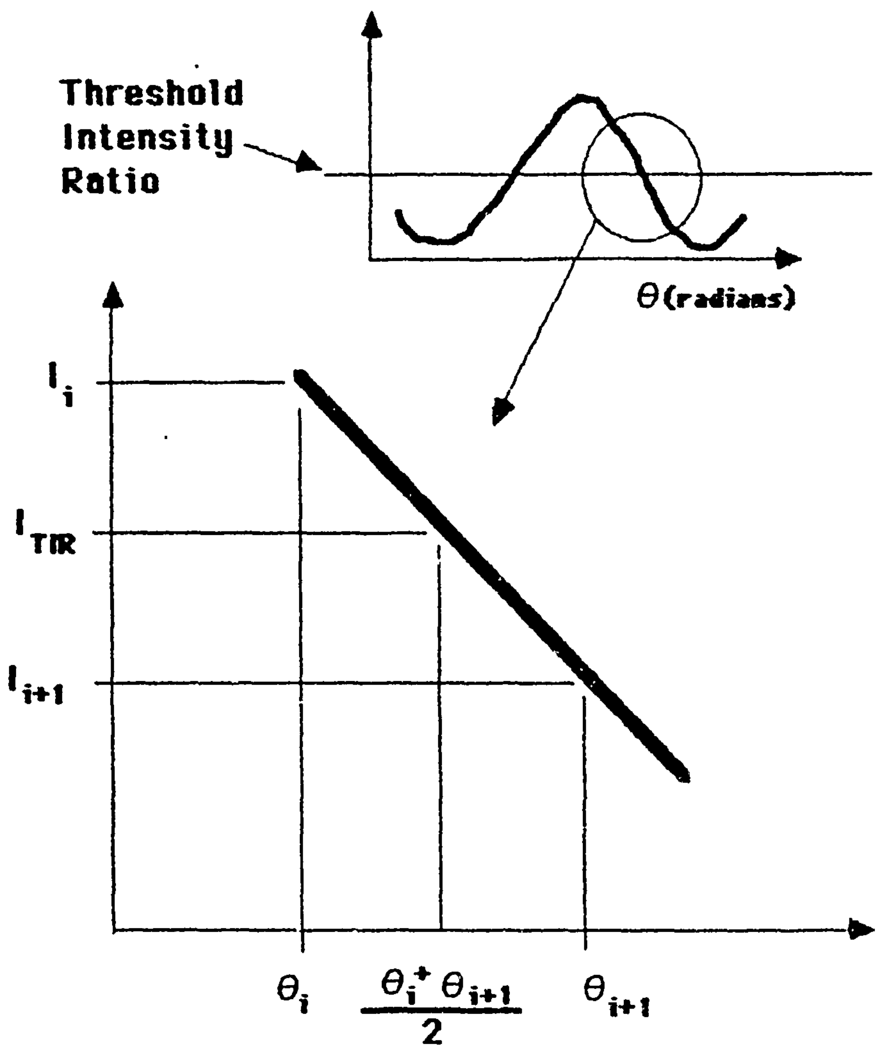


Figure 30. Averaging of Theta

3. INTRODUCTION OF ERROR INTO THE PERFECT DATA

EXPOSURE prompts the user for an error input. If error is desired, EXPOSURE calls the subroutine RANDOM. RANDOM introduces error based on the maximum intensity ratio in the perfect data:

$$I_{err} = I_{\theta} + [\ I_{max} * \text{ERROR} * \text{RND}\ ]$$

where ERROR is the error to be introduced and RND is a random number between ±1 generated by the NONIMSL subroutine RANDU. RANDOM returns the now "imperfect" intensity ratios to the EXPOSURE program.

C. DIGITIZATION PROBLEMS WITH THE IMPERFECT DATA

Digitizing the imperfect data results in local regions where the intensity oscillates between 0 and 1, as shown in Table 1. The introduction of random error changes the smooth curve to erratic points. Locally, variations above and below the threshold intensity ratio cause a series of 0-->1 and 1-->0 oscillations. (See Figure 31) Ideally, only one local theta location is to be associated with the threshold intensity ratio.

There are two approaches to this problem. First, the average of the local theta locations can be calculated. This method results in three theta locations for input into the DIAFIND program (the same as perfect data).

TABLE 1. DIGITIZATION ERROR

THETA LOCATION	INTENSITY RATIO	
0.2321624000E 00	0.3544308000E-04	1
0.2324997000E 00	0.3196243000E-04	1
0.2328373000E 00	0.3160309000E-04	1
0.2331748000E 00	0.3246925000E-04	1
0.2335124000E 00	0.3372986000E-04	1
0.2338498000E 00	0.3785736000E-04	0
0.2341873000E 00	0.3090432000E-04	1
0.2345249000E 00	0.3342219000E-04	1
0.2348623000E 00	0.3387519000E-04	1
0.2351998000E 00	0.3205373000E-04	1
0.2355374000E 00	0.3516222000E-04	1
0.2358747000E 00	0.3860490000E-04	0
0.2362123000E 00	0.3421140000E-04	1
0.2365499000E 00	0.3468163000E-04	1
0.2368872000E 00	0.3580747000E-04	1
0.2372248000E 00	0.3904779000E-04	0
0.2375622000E 00	0.3578593000E-04	1
0.2378997000E 00	0.3912353000E-04	0
0.2382373000E 00	0.3599435000E-04	1
0.2385748000E 00	0.3474336000E-04	1
0.2389124000E 00	0.3538676000E-04	1
0.2392498000E 00	0.3470230000E-04	1
0.2395873000E 00	0.3952176000E-04	0
0.2399249000E 00	0.3923[illegible]57000E-04	0
0.2402623000E 00	0.3944175000E-04	0
0.2405998000E 00	0.3966210000E-04	0
0.2409374000E 00	0.4409726000E-04	0
0.2412747000E 00	0.4269459000E-04	0
0.2416123000E 00	0.4371968000E-04	0
0.2419497000E 00	0.3904802000E-04	0

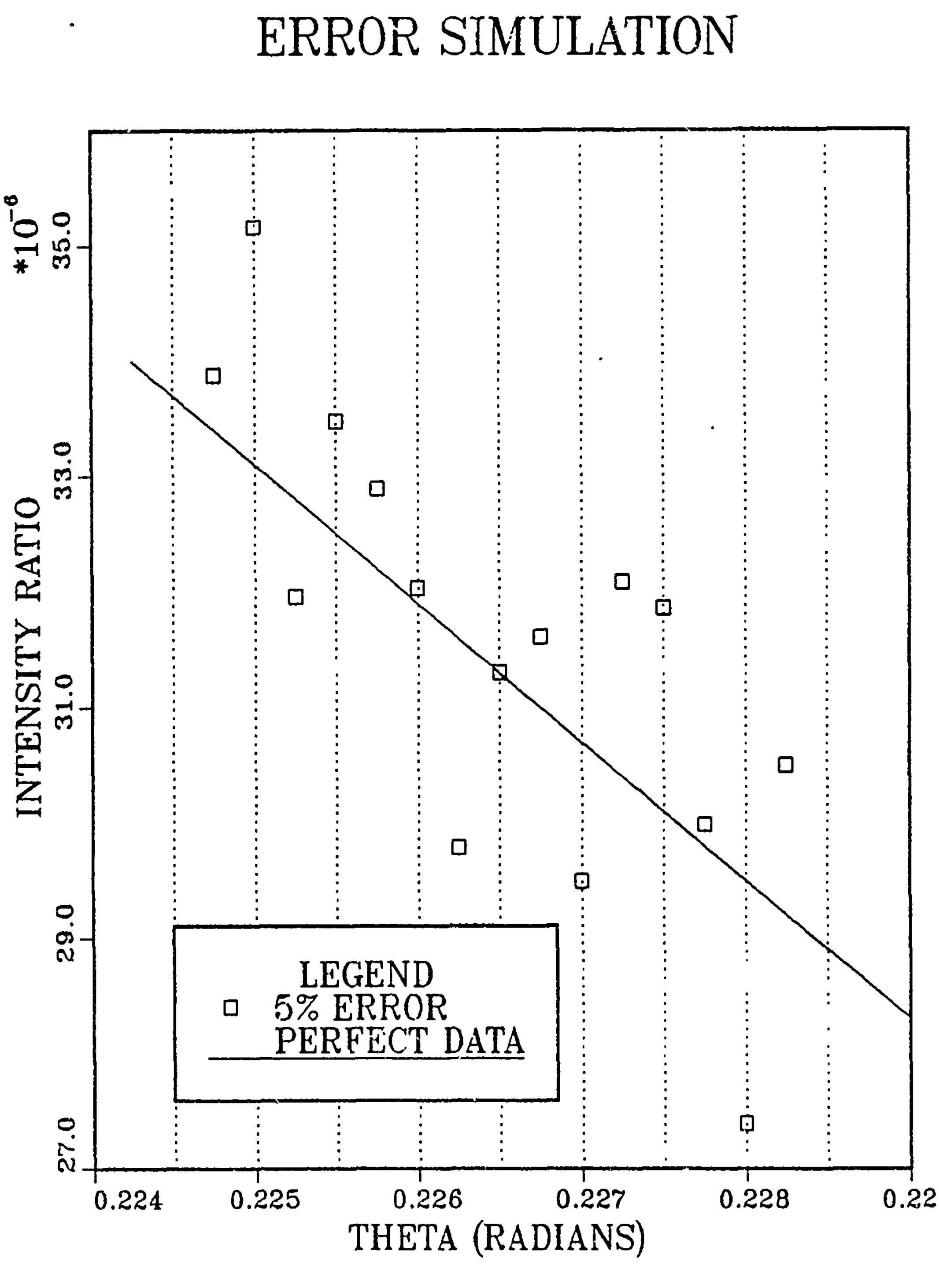


Figure 31. Intensity Variation at 5% Error

The second method is to accept the theta locations as they are and enter them into the DIAFIND program. The latter method will pass a variable number of data points to DIAFIND.

Both approaches were tested (at 5% error for 7.254 μm) and the same diameter was recovered by DIAFIND in each case. The only difference between the two methods is that the averaging method runs one second faster (out of 22 seconds on the IBM 360) than the other method.

The averaging method was adopted for this simulation for two reasons:

(1) The data input to DIAFIND will always be a constant number of points so that DIAFIND can be easily adapted to run actual Micron Eye data without simulation related logic buried in the code.

(2) The averaging method returns the same diameter as the other method.

D. CHOOSING THE CORRECT EXPOSURE (TUNING)

The optimum exposure for this simulation was calculated by the program EXPOSURE. It was an average value of the intensity ratios associated with the maximum derivatives locations for the 7.254μm fiber data. This same exposure was used throughout the simulation for all the fibers.

Using the same exposure introduces realism into the simulation since one cannot tune the exposure for every fiber that is to be measured. Because the Micron Eye window is located at least two nodes out from the central maximum the exposure is closer to optimum for all diameters over the range. (In contrast to a window location closer to the central maximum.)

The process EXPOSURE uses to determine the threshold intensity ratio can be called "tuning". The Micron Eye analog of tuning would consist of three steps:

(1) Determine the approximate diameter for the fiber to be measured using an optical shearing eyepiece.

(2) Determine the Micron Eye location parameters L and **x** by the methods in Chapter 5.

(3) Vary exposure to obtain a defined relationship between the three points on the Micron Eye photograph.

As an example, return to the case where $L = 30$ mm and $x_{inner} = 5$mm. (x_{inner} is the inboard x location of the Micron Eye array.) Figure 32 shows the "tuned" relationship between three points on the Micron Eye array. This relationship can be expressed as a ratio of **a** : **b** : **c**. The theta locations at the inboard and outboard edges of the Micron Eye are known.

e.g., $\theta_{inner} = .165$ radians and $\theta_{outer} = .300$ radians.

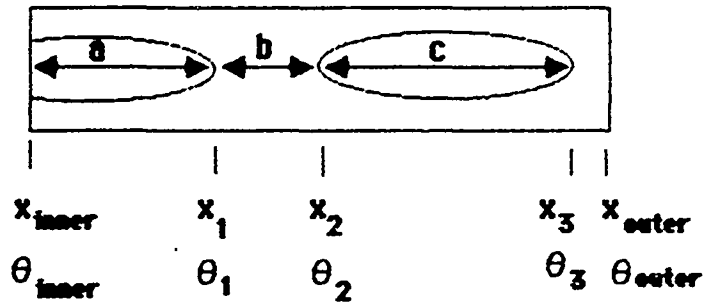


Figure 32. Three Point Spacing Ratio

This means that $\theta_{inner} < \theta_1 < \theta_2 < \theta_3 < \theta_{outer}$.

To find θ_1, θ_2, and θ_3; run EXPOSURE for the diameter being tuned. EXPOSURE outputs the theta values for the optimum exposure. (See Figure 33)

The theta values are related to x locations by:

$$x_1 = L\tan(\theta_1)$$
$$x_2 = L\tan(\theta_2)$$
$$x_3 = L\tan(\theta_3)$$

where

$$a = x_1 - x_{inner}$$
$$b = x_2 - x_1$$
$$c = x_3 - x_2$$

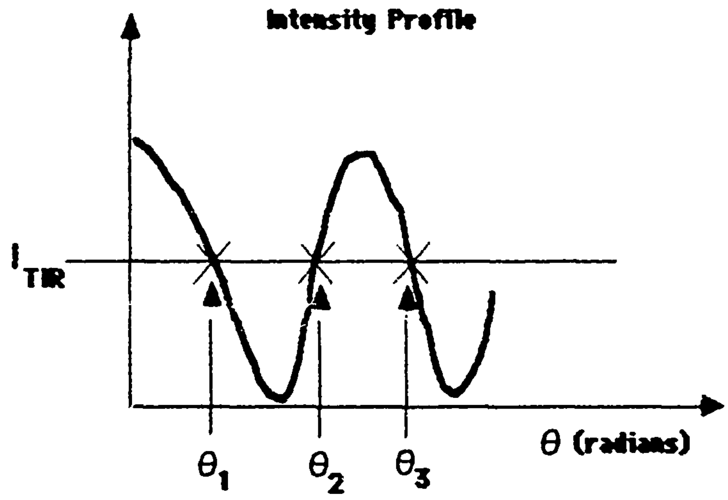


Figure 33. Finding the Theta Locations

VII. DISCUSSION OF RESULTS

The simulation was conducted for three diameters:

$d_1 = 5.803\ \mu m$

$d_2 = 7.254\ \mu m$

$d_3 = 8.705\ \mu m$ (where d_1 and d_3 are ±20% d_2)

For each $\mathbf{d_i}$, three levels of error were introduced: 1%, 2% and 5%.

Figure 34 shows the three intensity profile curves for the $\mathbf{d_i}$.

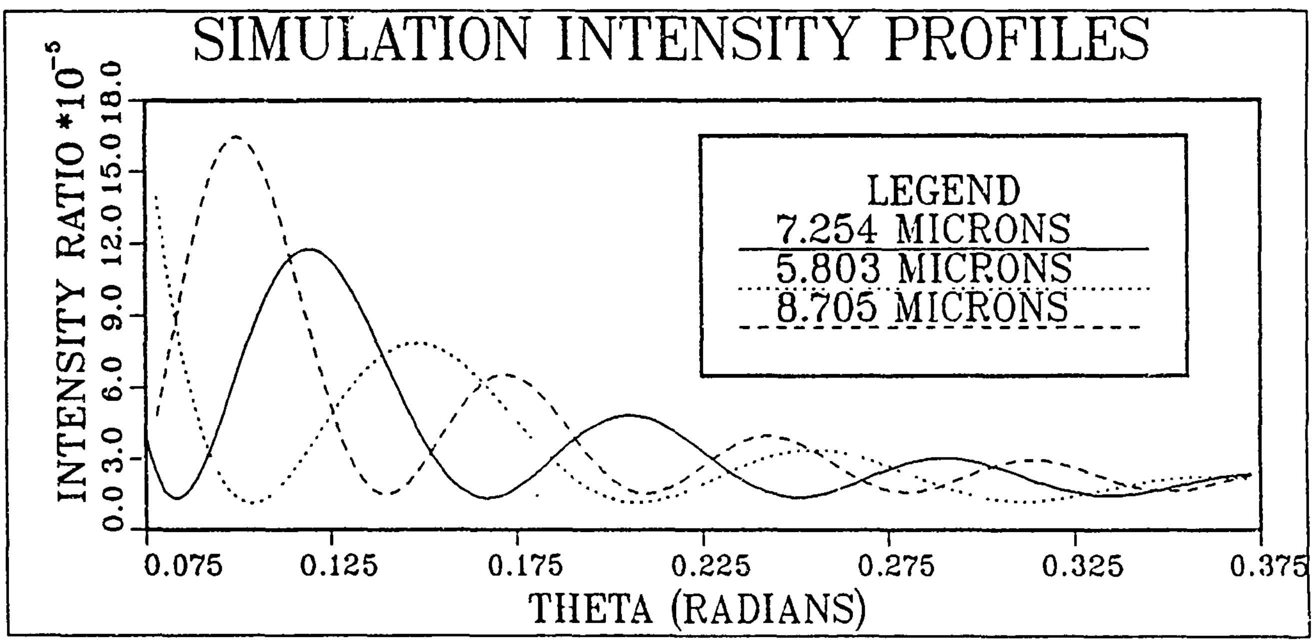


Figure 34. Simulation Intensity Profiles

The simulated Micron Eye window was determined as previously described at L = 30mm and x_{inner} = 5mm. The exposure was tuned with respect to the 7.254µm perfect data. EXPOSURE recommended the Threshold Intensity Ratio of .0000370. This Threshold Intensity Ratio remained constant throughout the simulation, for all diameters.

Before the simulation, all diameters were tested with <u>no</u> error using the 7.254µm Threshold Intensity Ratio. DIAFIND recovered $\mathbf{d_1}$, $\mathbf{d_2}$ and $\mathbf{d_3}$ exactly (i.e., to the three digits accuracy of the original diameters).

The simulation originally began by collecting thirty data points for each diameter/error combination. Twenty additional points were collected (50 total) to produce meaningful histograms.

Figures 35 through 43 are histograms depicting the results of the simulation. In general, the expectation was to see a decrease in resolution as more error was introduced. It was also anticipated the resolution would be best for the 7.254µm case (for all values of error) since the exposure was "tuned" for this diameter. Finally, it was hoped the method would be more accurate than existing laser diffraction measurement methods ($\approx$ 0.5%).

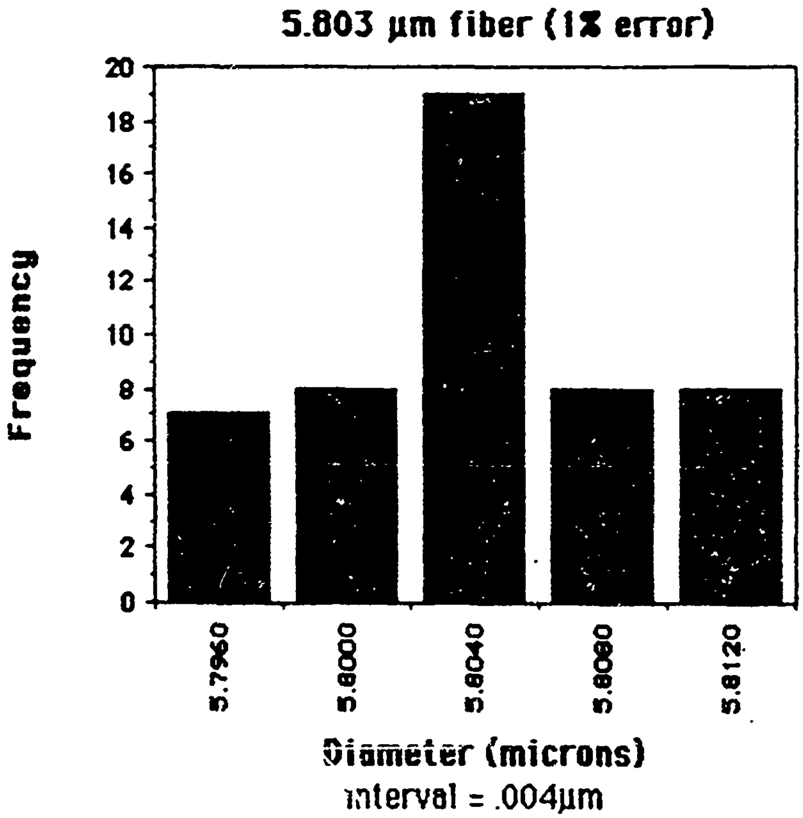


Figure 35. 5.803µm Fiber (1% error)

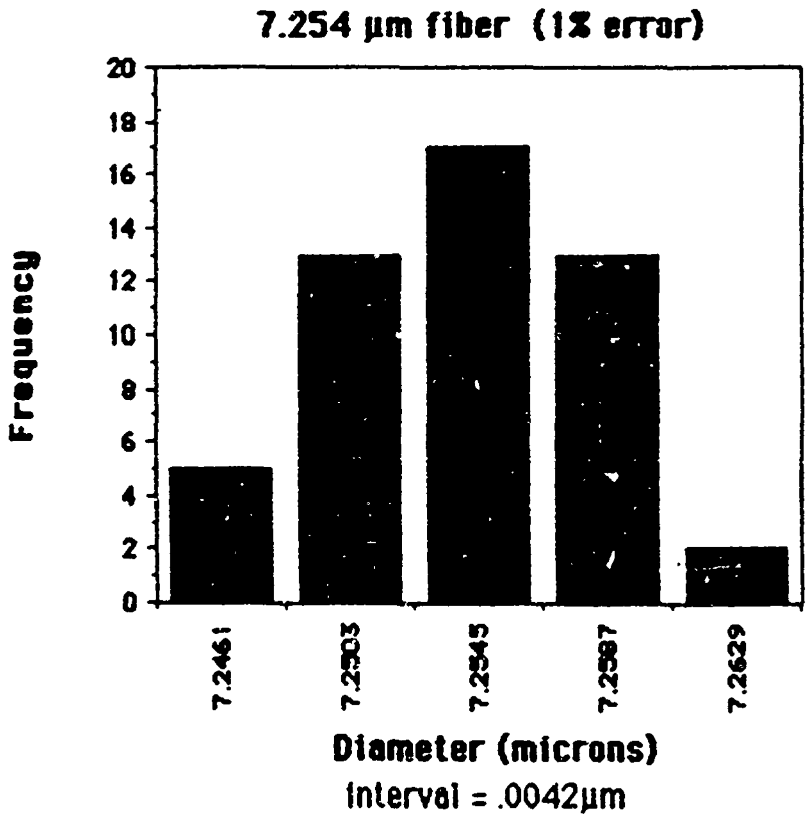


Figure 36. 7.254µm Fiber (1% error)

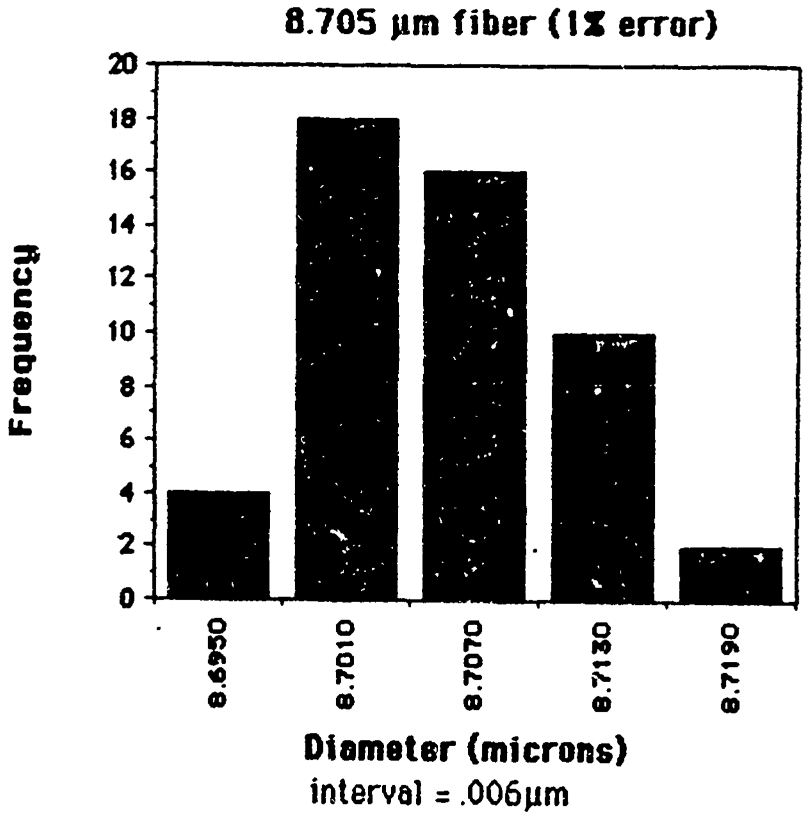


Figure 37. 8.705µm Fiber (1% error)

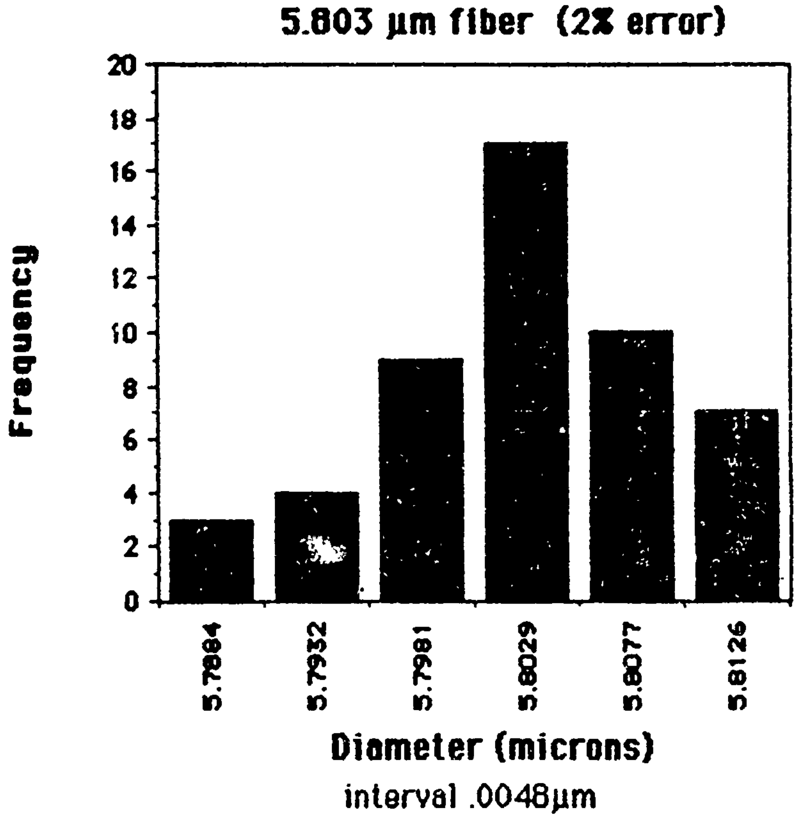


Figure 38. 5.803µm Fiber (2% error)

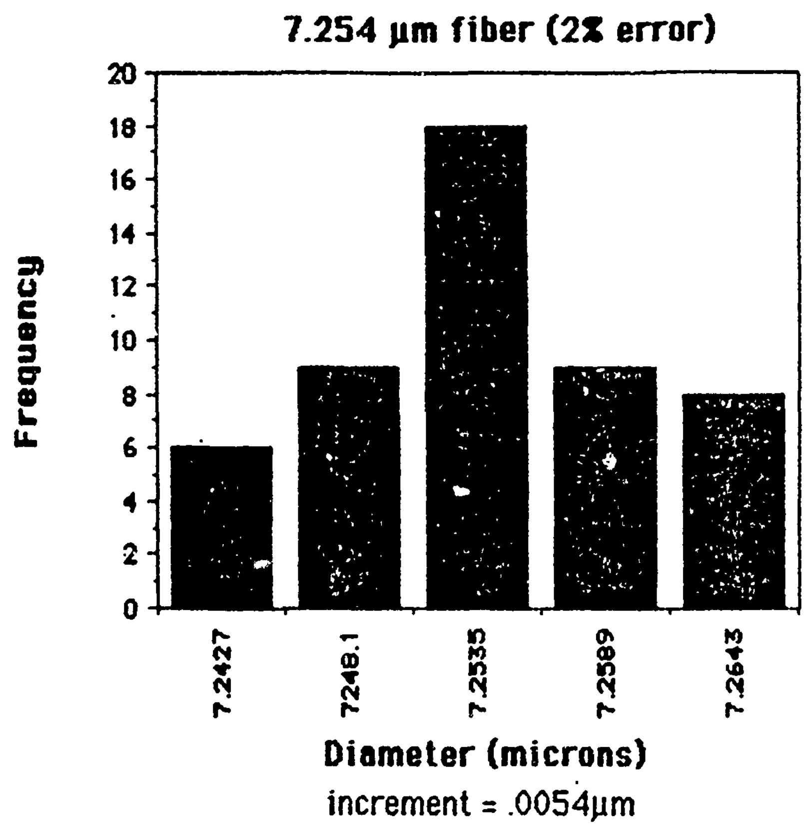


Figure 39. 7.254µm Fiber (2% error)

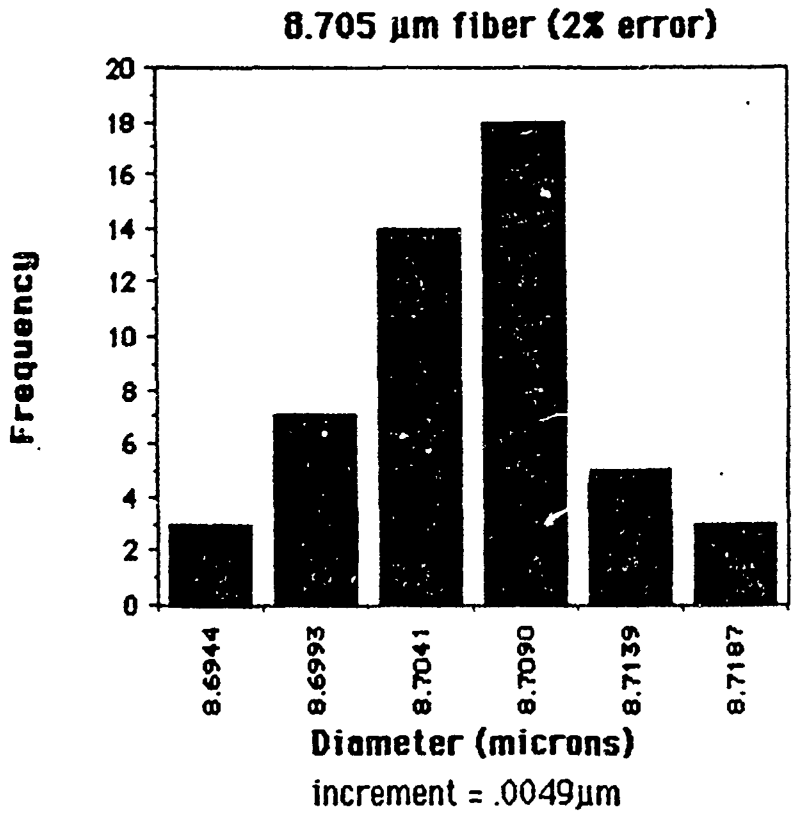


Figure 40. 8.705µm Fiber (2% error)

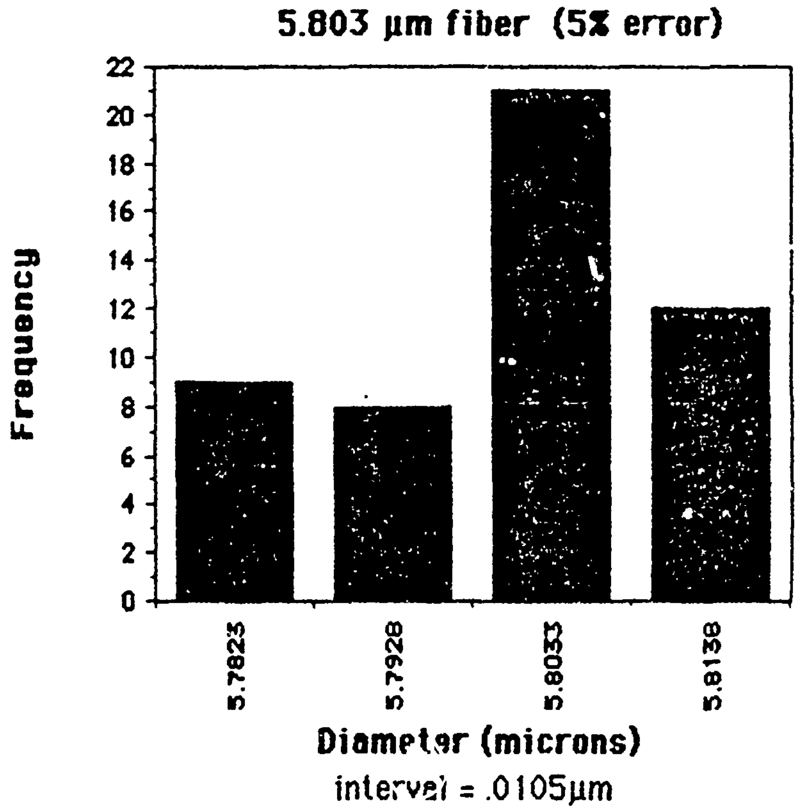


Figure 41. 5.803µm Fiber (5% error)

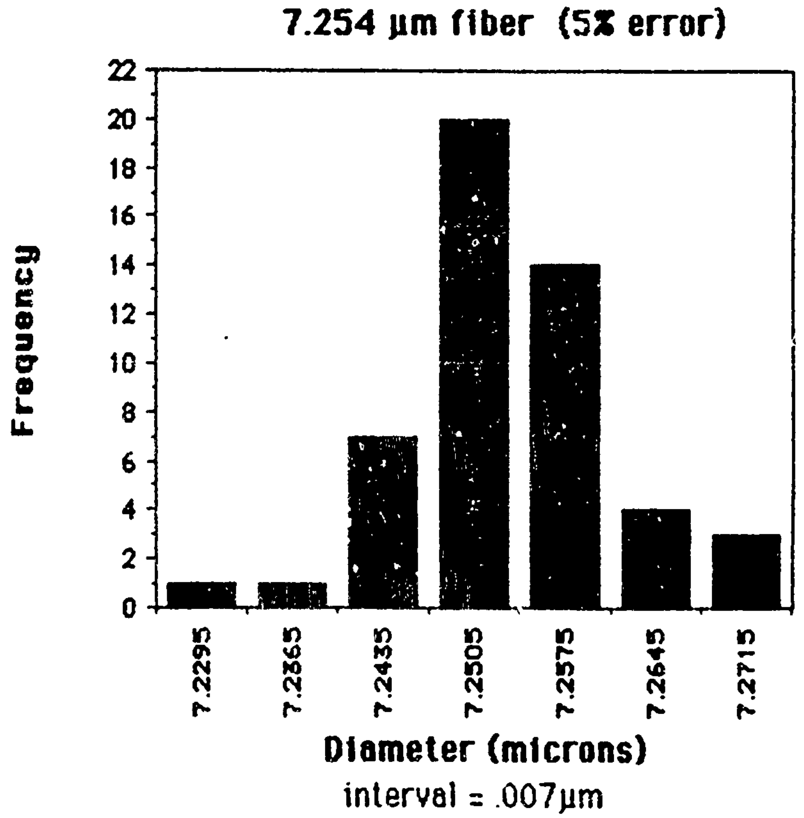


Figure 42. 7.254µm Fiber (5% error)

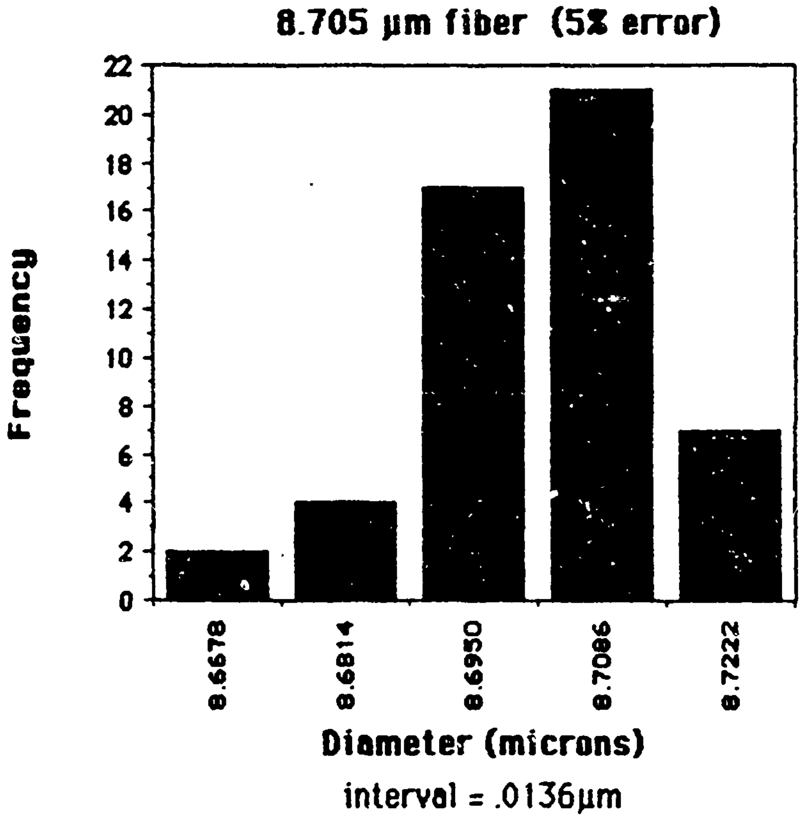


Figure 43. 8.705µm Fiber (5% error)

A. ACCURACY VERSUS RESOLUTION

The histrograms show the accuracy and the resolution of the method. The accuracy is associated with the largest spike, and related to the size of the interval called the resolution. The resolution is the ability of the routine to "see" a difference between two different fibers. For example, if the resolution is .005µm the method does not discriminate between 8.705µm and 8.700µm. Table 2 shows accuracy versus resolution for the results.

Table 2. ACCURACY VERSUS RESOLUTION

%ERROR	DIAMETERµm	RESOLUTION	ACCURACY (Res/d_{act}) %
1	5.803	.004	.069
	7.254	.0042	.058
	8.705	.0060	.069
2	5.803	.0048	.083
	7.254	.0054	.074
	8.705	.0049	.056
5	5.803	.0105	.181
	7.254	.0070	.096
	8.705	.0136	.156

The data show a decrease in accuracy and resolution as error is increased. It is evident in most cases that the 7.254µm results are better because it was the "tuned" diameter. The only exception is the accuracy for the 8.705µm fiber (2% error) is better than the 7.254µm fiber. Overall, the largest error is .18 percent which is less than one half of the error associated with the manual laser diffraction method.

B. ERROR

There are two contributions to error in this simulation.

The first can result from programming/calculation errors. Many trial runs of the software were taken to minimize the likelihood of this kind of error.

The next type of error is the digitizing error encountered in an actual experiment. This error is simulated based on the maximum intensity of the profile curve, in the region of interest, to apply random error equally to all points. Had the random error been based on each point, points with less intensity would have less error, and points with higher intensity more error, which is inconsistent with the physical digitizing process. Using the maximum intensity avoided such a condition but it cannot be ascertained that this is the optimal representation of the physical system.

VIII. CONCLUSIONS

The results of the simulation are encouraging. The largest error is .18% or less than one half of the manual methods. Because the programs were carefully developed and tested it is unlikely they contri' 'ted to the error. Also, much effort was directed towards accurate simulation of the physical system so that the results would reflect what can be expected from the actual experimental measurements.

The simulation demonstrates an increase in accuracy two to ten times better than that currently possible by making manual measurements with laser diffraction. The method also lends itself to automation which makes it attractive for quality control purposes and research for materials development.

IX. RECOMMENDATIONS

This study has shown the feasibilty of computer aided diameter measurements. There are many directions future work can take.

A. SOFTWARE.

More development and testing of the software could result in increased accuracy. It would also be valuable to implement the software on a small computer (like the Macintosh) to allow real time processing of actual data.

B. HARDWARE.

There remain some hardware considerations which must be resolved. The biggest of these, perhaps, is the accurate positioning of the Micron Eye array in the direction perpendicular to the laser beam. In an effort to increase the resolution and accuracy of the problem, the system may benefit from two Micron Eyes.

APPENDIX A. FRAUNHOFER DIFFRACTION THEORY

The following is a brief discussion of Fraunhofer diffraction theory with emphasis on aspects of the theory which relate to this research.

A. FRAUNHOFER DIFFRACTION

Fraunhofer diffraction (Figure 44) results when light approaches and leaves an obstacle or aperture in the form of plane wavefronts. [Ref. 4:p. 176] The light source and the plane of observation in effect are at infinity. A collimated laser beam is ideally capable of Fraunhofer diffraction because its beam consists of parallel rays advancing in phase.

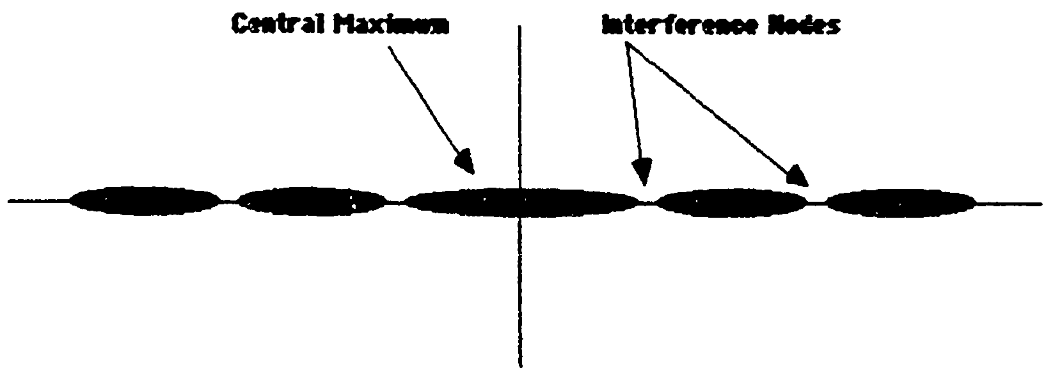


Figure 44. Typical Single Slit Diffraction Pattern

B. THE CLASSICAL SINGLE SLIT EXPERIMENT

The simplest demonstration of Fraunhofer diffraction is the single slit experiment. (See Figure 45) Parallel, co' imated light passes through a slit of width **a**. The diffraction pattern is visible on a screen located a distance L from the slit. An observer at point **P**, moving across the screen, sees a succession of maximum and minimum intensity points. These extrema are the result of constructive and destructive interference of the light. For example, a minimum occurs when the angle θ produces a phase difference of one wavelength between the rays at the upper and lower edges of the slit. Thus, minima occur whenever

$$\mathbf{a}\ \mathbf{sin}(\theta) = \mathbf{m}\lambda, \quad \text{where } m = 1, 2, 3 \ldots\ldots \qquad \mathbf{(A.1)}$$

These minima are referred to as interference nodes. (For further discussion of this subject, see Meyer-Arendt, [Ref. 4].)

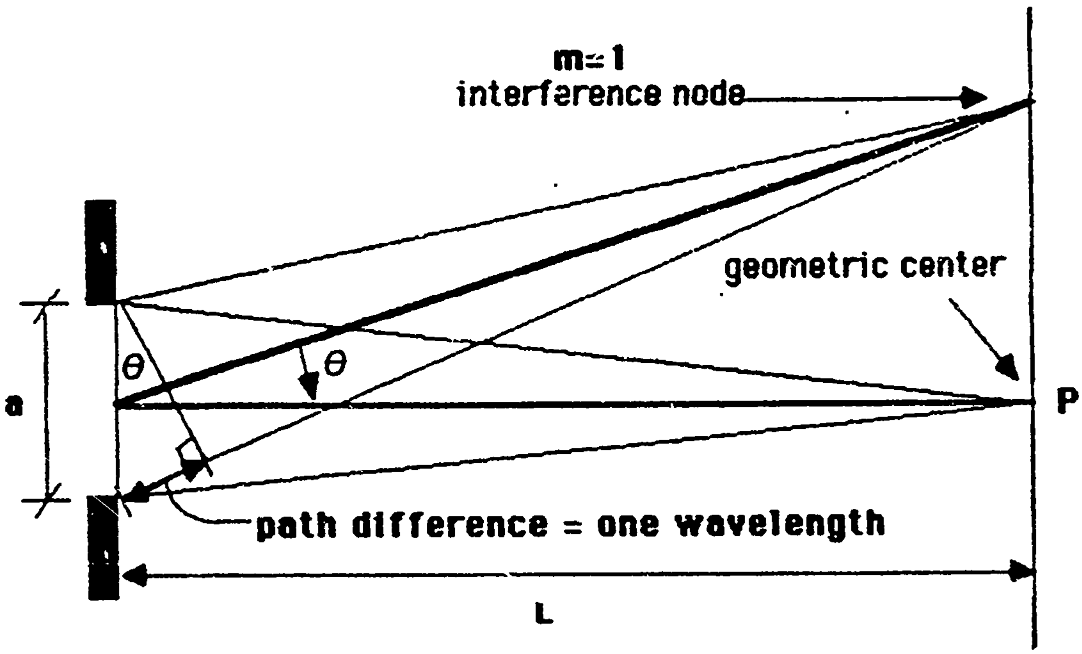


Figure 45. Single Slit Path Difference Relation to the Interference Node

1. Diffraction Minima

Examination of equation (A.1) shows that as the slit becomes narrower the angle θ becomes larger. As this theory is extended to approximate the diffraction phenomena of an obstruction (a fiber), one can expect short distances between interference nodes for larger fibers and greater distances between nodes for fibers of smaller diameters.

Another important point concerns the distance between minima. It appears the interference nodes are equidistant. This is true only within the limits of the small angle approximation. The distances between interference nodes actually increases as one moves outward from the central maximum by the relation:

$$\theta_{min} = \sin [m\lambda/d] \qquad \text{(A.2)}$$

2. Diffraction Maxima

The diffraction maxima are not located midway between minima. The locations of the maxima can be derived as by Meyer-Arendt [Ref. 7:p. 220]. These occur whenever the derivative of the intensity is equal to zero:

$$dI/d\beta = dI/d\beta \left[I_o (\sin \beta/\beta)^2 \right] = 0$$

$$= 2I_o \sin\beta/\beta \left[-\sin\beta/\beta^2 + \cos\beta/\beta \right]$$

or whenever: $\beta = \tan\beta$ (A.3)

$y=\tan\beta$ and $y=\beta$. (See Figure 46) The maxima are displaced slightly from center towards the central maximum. Much further away from the central maximum, the maxima are nearly halfway between minima.

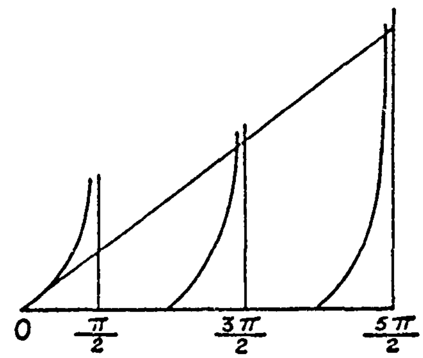


Figure 46. Locations of the Diffraction Maxima

C. FRAUNHOFER DIFFRACTION AND THE FOURIER TRANSFORM

The foregoing discussion centered on the Fraunhofer diffraction due to a slit. The mathematics of the slit example are simple and provide insight into diffraction physics. A more elegant derivation of Fraunhofer diffraction shows that the diffraction pattern of an object is the Fourier transform of that object. [Ref. 9:p. 174]

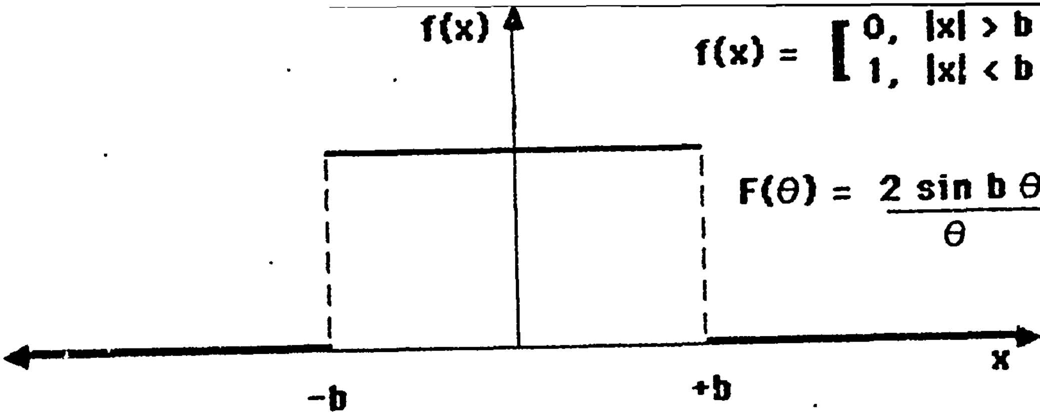


Figure 47. Fourier Transform for the Single Slit

Thus, $F(\theta)$ describes the amplitude of the diffraction pattern, and $[F(\theta)]^2$ represents the intensity.

Modeling the transform for the obstruction is more complicated. consider the complement of the slit transform: $g(x) = 1 - f(x)$.

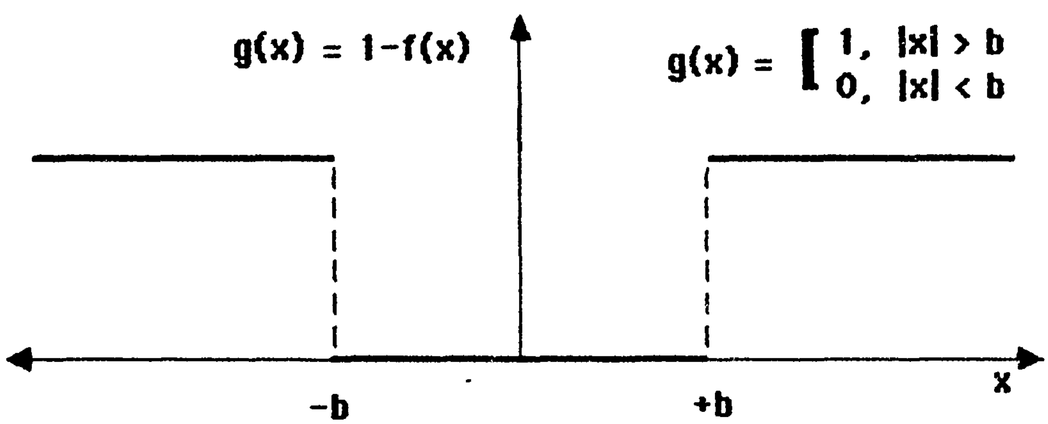


Figure 48. Complement of the Fourier Slit Transform

This results in the form $[\ \infty\ -\ 2\sin(b\theta)/\theta\ ]$ which is not transformable.

An alternative is to use a substitute function $h(x) = g(x) - f(x)$. Physically, this is approximating the obstruction as two parallel slits:

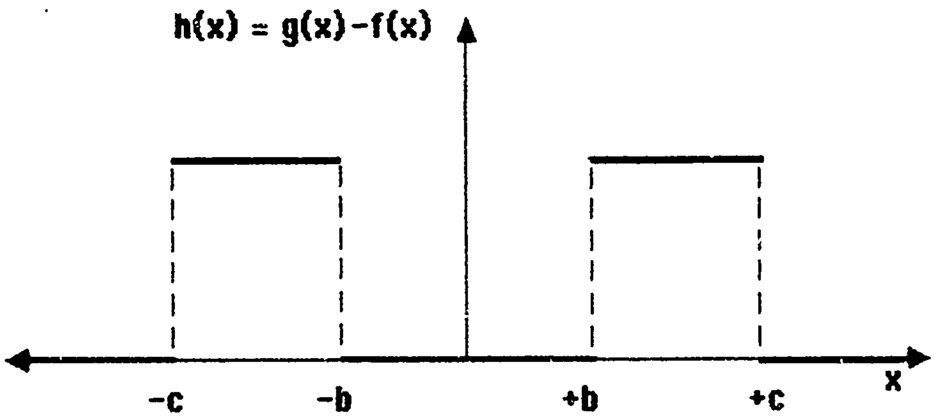


Figure 49. Fourier Transform for Two Parallel Slits

which has the solution:

$H(\theta) = (2\sin c\theta)/\theta \ - \ (2\sin b\theta)/\theta$

where **c** would be large, but not infinite.

This is still a crude approximation which shall be improved upon in the next section.

D. REJECTION OF THE SLIT APPROXIMATION

In their paper titled "Fiber Diameter Measurement by Laser Diffraction" [Ref. 3:p. 1378], Perry, Ineichen, and Eliasson conclude that the diffraction pattern of a real fiber is sufficiently different from that of a slit to warrant the slit approximation being treated with caution.

Further, they recommend a solution presented by Kerker [Ref.5:p. 260] which has been adopted in this study. Kerker's solution assumes the fiber is perfectly reflecting (i.e.,the reflective index $m=\infty$), and while this is not completely true, Perry, et al., [Ref. 3:p. 1378] indicate some degree of absorption is not likely to be significant.

E. INTENSITY EQUATION FOR A REAL FIBER

Kerker [Ref. 5:p. 260] gives the scattered intensity relation for a real fiber:

$$I/I_o = (2/K_o L\pi) \left| b_o + 2 \sum b_n \cos(n\theta) \right|^2 \qquad \text{(A.4)}$$

where $\theta =$ the scattering angle

$K_o = 2\pi / \lambda$ (λ = laser wavelength)

$b_n = J_n(\alpha) / H_n^{(2)}(\alpha)$

and $\alpha = \pi d_f / \lambda$ (d_f = fiber diameter)

$J_n(\alpha)$ are Bessel functions of the first kind,

$H_n^{(2)}(\alpha)$ are Hankel functions of the second kind.

The real fiber equation (A.4) is somewhat obscure in its compact form. It can be shown that:

$$I/I_o = (2/K_o L\pi)\left[\left(r_o + 2\Sigma\, r_n \cos(n\theta) \right)^2 + \left(s_o + 2\Sigma\, s_n \cos(n\theta) \right)^2\right] \quad \text{(A.5)}$$

where $$r_n = J_n^2(\alpha) \;/\; [\, J_n^2(\alpha) + Y_n^2(\alpha)\,] \quad \text{(A.6)}$$

and $$s_n = J_n(\alpha)\, Y_n(\alpha) \;/\; [\, J_n^2(\alpha) + Y_n^2(\alpha)\,] \quad \text{(A.7)}$$

Now, the intensity ratios for any θ location can be calculated for any diameter fiber.

1. Sensitivity of the Results to the Number of Bessel Terms

The calculation of Intensity Ratios requires the computation of **n** r_n and s_n Bessel terms, equations (A.6) and (A.7). Here the phrase "Bessel terms" indicates the algebraic combinations of the J_n and Y_n Bessel functions.

a. Two competing phenomena

There exist two competing phenomena which govern the number of Bessel terms to be used in the calculations. The first requires a minimum number of terms for accuracy. The second, limits the number of terms so the Y functions do not cause an underflow error during computation.

(1) Minimum Number of Terms. As in any series, there is a minimum number of terms required for computational accuracy. Figure 50 shows the effect of the number of Bessel terms computed for seven curves, all with a diameter of eight microns.

Note that the 43, 50, 75, and 86 term curves are nearly identical and the curves with fewer than 43 terms are decreasing towards a smooth line. This research, indicates that 50 terms returns four digit accuracy for diameters ranging from 5 to 10 microns.

(2) Maximum Number of Terms. The maximum number of terms depends on the value of α. As the diameter decreases, so does α. This in turn produces very large values of $Y_m^2(\alpha)$ (in the r_m and s_m denominator) which causes an underflow error. For the diameter range considered in this research, underflow was not a problem. In one instance, below 5 microns, it was found the number of Bessel terms had to be reduced to 43 to prevent underflow. The effects of the minimum number of terms was not investigated at this smaller diameter range.

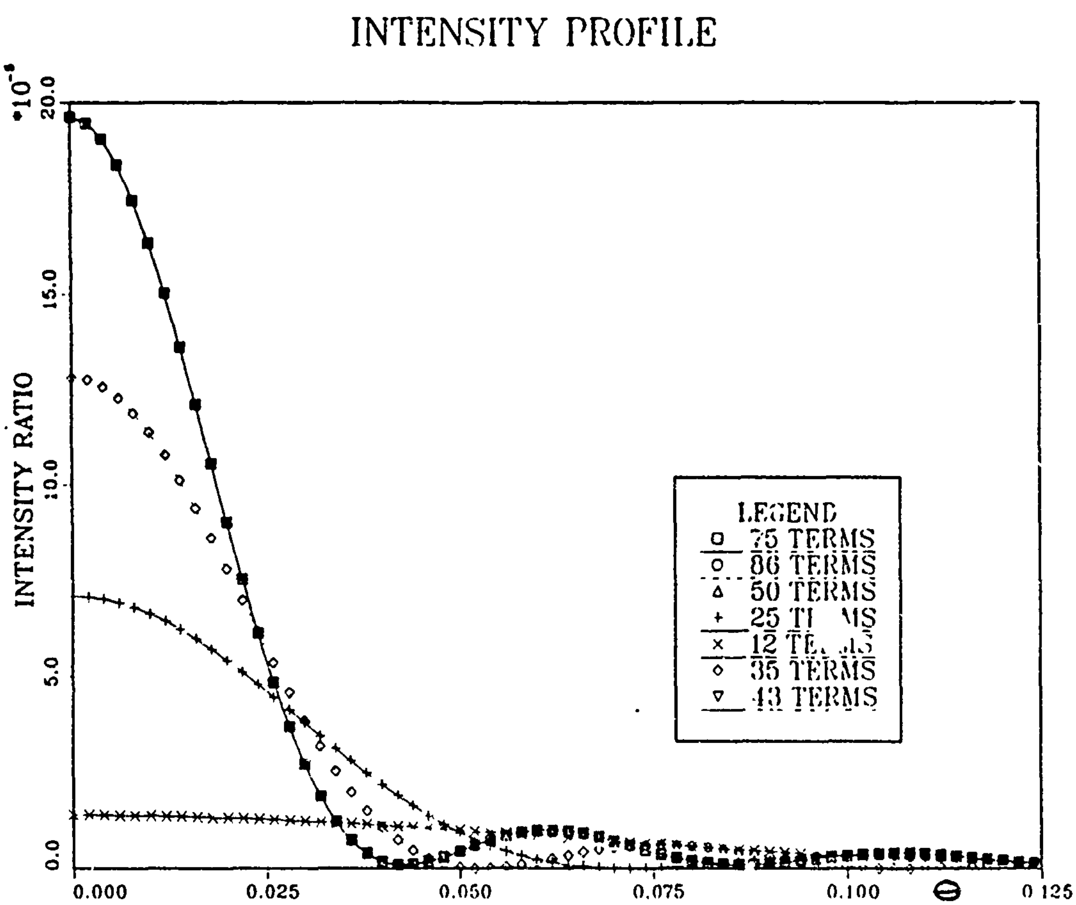


Figure 50. Effect of Number of Bessel Terms

2. Effect of Different Diameters

Recall that the diffraction pattern for a slit showed that as the diameter decreased, the interference nodes moved away from the center of the pattern. It is interesting to note that the pattern for a real fiber behaves the same way. (See Figure 51)

INTENSITY PROFILES

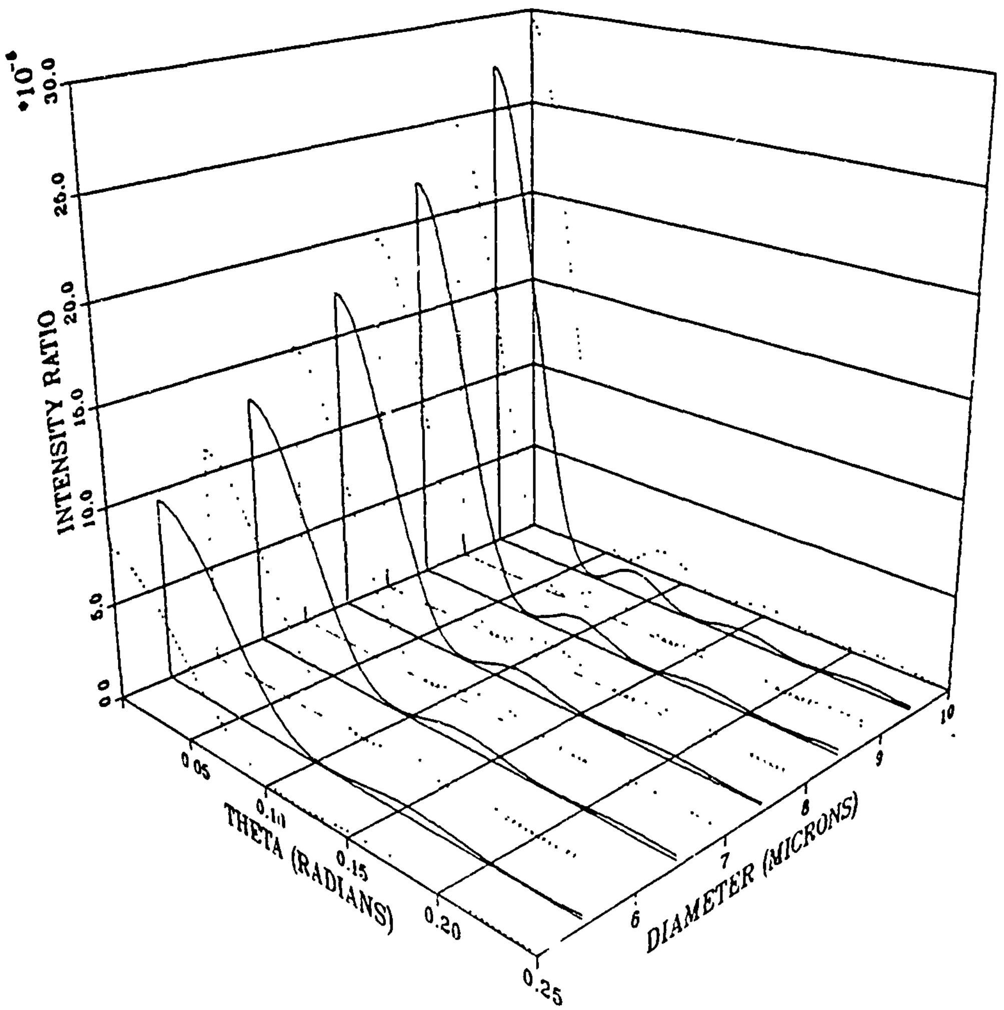


Figure 51. Effect of Different Diameters

APPENDIX B. COMPUTER PROGRAMS

The following is a list of programs discussed in this Appendix:

DATAMAKR

DIAFIND

EXPOSURE

The programs are written in Waterloo Fortran IV (WATFIV) and run on the Naval Postgraduate School's IBM 360 computer.

A. FORMAT OF DATA

All data is formatted using exponential notation. The most frequently manipulated files are those containing theta locations and intensity ratios. The format for these files is: (1X, E17.10, 1X, E17.10). In WATFIV all data files must be of filetype "WATFIV".

To compile and run a program on the IBM 360 type " WATFIV PROGNAME DATAFILE *(XTYPE", where PROGNAME is the filename of the program and DATAFILE is the filename of the data file.

B. COMPUTER PROGRAMS

This appendix presents the various computer programs and outlines their logic.

1. DATAMAKR

DATAMAKR generates the data used in the simulation. The equation for computing the Intensity Ratios of the diffraction pattern for any value of theta is:

$$I/I_o = (2/K_o L\pi) \left| b_o + 2 \sum b_n \cos(n\theta) \right|^2 \qquad \text{(A.4)}$$

where θ = the scattering angle

$K_o = 2\pi / \lambda$ (λ = laser wavelength)

$b_n = J_n(\alpha) / H_n^{(2)}(\alpha)$

and $\alpha = \pi d_f / \lambda$ (d_f = fiber diameter)

$J_n(\alpha)$ are Bessel functions of the first kind,

$H_n^{(2)}(\alpha)$ are Hankel functions of the second kind.

All computations begin by calculating the required number of Bessel terms. Two NONIMSL subroutines are called: BESJ for the $J_n(\alpha)$ and

BESY for the $Y_m(\alpha)$. Note: should double precision be desired, the NONIMSL subroutine BINT will return double precision values for the J_m and Y_m.

The Bessel function values are stored in an vector **J(I)** and **Y(I)**, and are used to calculate values of **R(I)** and **S(I)**. Next, the matrix of cosines is contructed. The size of this matrix is **M** by **K**, where **N** = **M-1** and **N** is the number of Bessel terms. **K** is the number of theta locations. Values of theta at each location have previously been stored in an array called **T(K)**.

To visualize the program's calculations, the matrices symbolic of these calculations are sketched. (See Figure 52) Note that r_o and s_o are outside the summation term in equation (A.1) and therefore will not be multiplied with any cosine terms. Since array subscripts must be designated with a nonzero value, r_o and s_o will be represented by **r(1)** and **s(1)**.

After multiplying the two matrices, it is necessary to complete the summation by summing the columns in the matrix. This results in an **N** term value for each value of theta. A straightforward calculation then yields the intensity ratios. The intensity ratios are stored in an array with their corresponding theta locations.

$$
\begin{bmatrix} r_2 \\ r_3 \\ r_4 \\ \vdots \\ r_m \end{bmatrix}
\times
\begin{bmatrix}
\cos\theta_1 & \cos\theta_2 & \cdots & \cos\theta_k \\
\cos 2\theta_1 & \cos 2\theta_2 & & \cos 2\theta_k \\
\cos 3\theta_1 & \cos 3\theta_2 & & \cos 3\theta_k \\
\vdots & \vdots & & \vdots \\
\cos(m-1)\theta_1 & \cos(m-1)\theta_2 & \cdots & \cos(m-1)\theta_k
\end{bmatrix}
$$

$$
[R] \times [C] = \begin{bmatrix}
r_2 c_{11} & \cdots & r_2 c_{1k} \\
r_3 c_{21} & & \\
r_4 c_{31} & & \\
\vdots & & \vdots \\
r_m c_{m-1,1} & \cdots & r_m c_{m-1,k}
\end{bmatrix}
$$

$$
\downarrow
$$

$$
\sum_{n=1}^{m} r_n \cos(n\theta_k)
$$

Figure 52. DATAMAKR Matrix Algebra

The logic of DATAMAKR is:

Input -----> # Bessel terms to be computed
diameter of the fiber
screen to fiber distance, L
array of theta location values

Calculate: R_n and S_n using BESJ and BESY

Produce the Matrix of Cosines

Produce the Matrix of Products

Sum the columns of the Product Matrix

Compute and output the Intensity Ratios

2. DIAFIND

This program finds the diameter of a fiber through an iterative process of residual comparison. The program accepts the data which has been output by the program EXPOSURE. The user is prompted for **K** and $\mathbf{d_i}$. **K** is the number of theta values the program should expect and $\mathbf{d_i}$ is the initial guess of the fiber diameter (in microns).

The program first calculates intensity ratios at the diameter $\mathbf{d}_i$, corresponding to the input theta locations. The difference between the input intensity ratios and those associated with $\mathbf{d}_i$ is called the residual. The program calculates another set of intensity ratios based on a new diameter $\mathbf{d}_i + \Delta\mathbf{d}_i$, where $\Delta\mathbf{d}_i$ is a small increment of diameter (usually .05 microns to start). The intensity ratios calculated using $\mathbf{d}_i + \Delta\mathbf{d}_i$ are compared with the input intensity ratios to give a second residual. The residuals are compared and program logic determines whether or not the $\Delta\mathbf{d}$ increment is producing convergence to the actual diameter. The initial guess diameter is incremented and decremented as necessary until a desired level of accuracy is achieved.

A key to understanding the convergence process is the residual curve in Figure 53. It is important that the initial guess, $\mathbf{d}_i$, be fairly close to the actual diameter.

For example, the residual curve in Figure 53 is for an actual diameter of 7 microns. If $\mathbf{d}_i$ is greater than 9 microns, the program will not converge to the correct diameter, but rather to a diameter just above 10 microns.

It is hard to define exactly the limits of $\mathbf{d}_i$ for any given actual diameter. Figure 54 is a residual curve for 5 microns and shows an upper limit of 9 microns for d_i. A thorough study to define limits for d_i has not been conducted, although convergence has always been attained by guessing d_i within ±1 micron for diameters ranging from 5 to 9 microns.

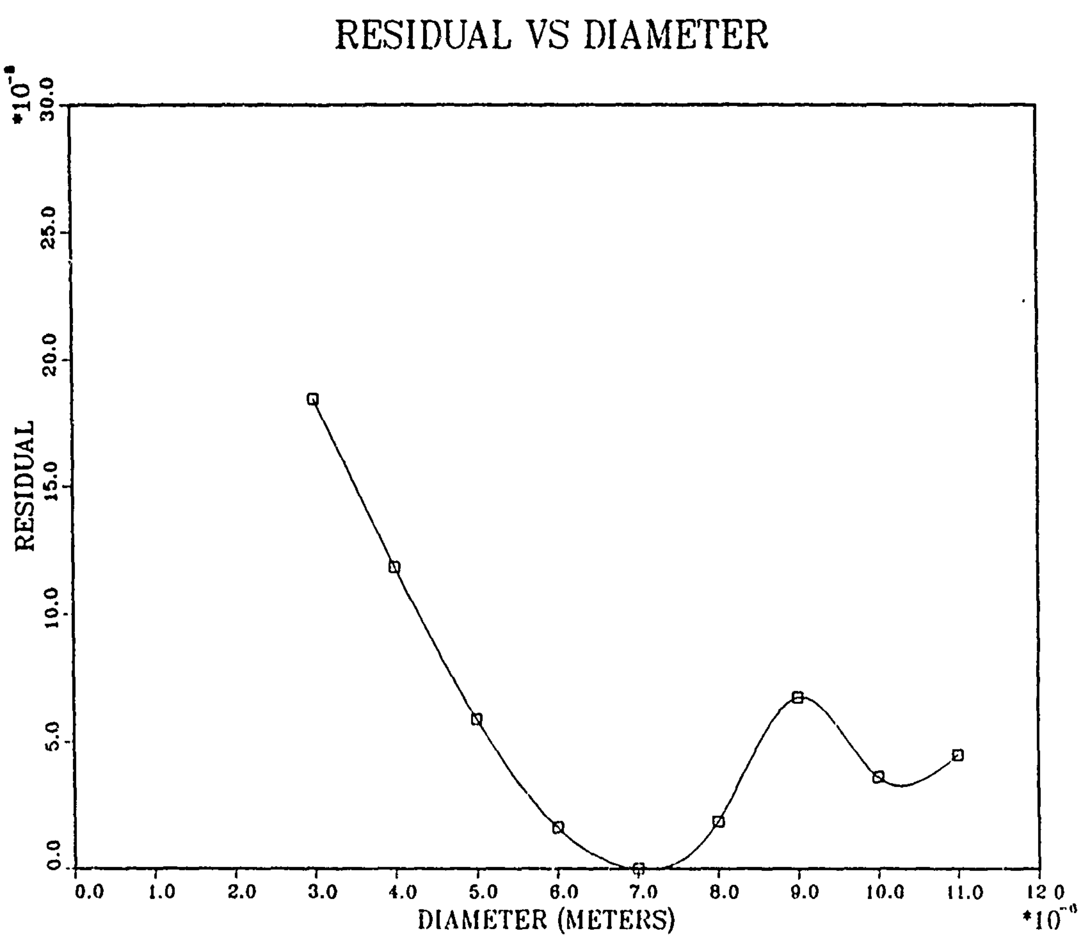


Figure 53. Residual Versus Diameter for 7µm Fiber

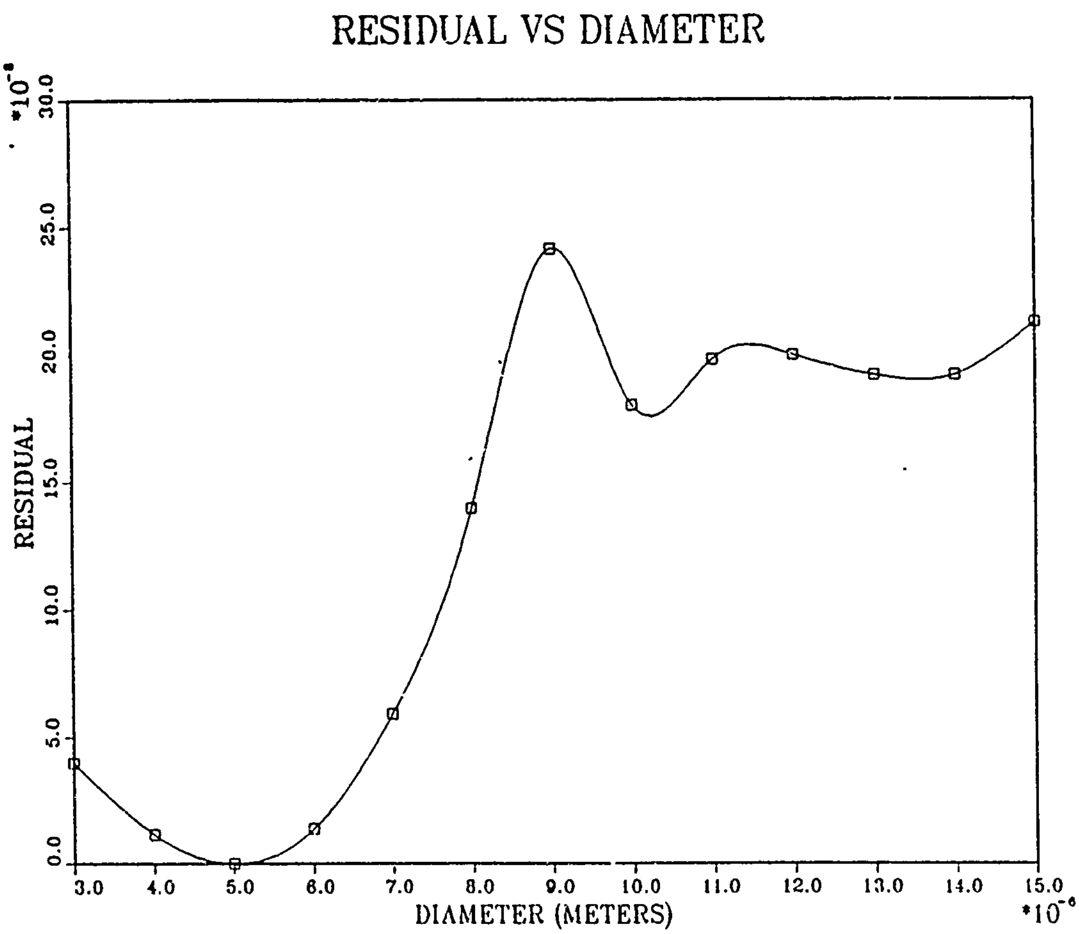


Figure 54. Residual Versus Diameter for 5μm Fiber

3. EXPOSURE

EXPOSURE simulates the operation of the Micron Eye by taking a photograph of intensity ratio data. EXPOSURE reads in the perfect data generated by DATAMAKR and digitizes the data with respect to a threshold intensity ratio.

The optimum intensity ratio for an exposure is termed the **threshold intensity ratio**. The threshold intensity ratio is located where the absolute value of the derivative of the intensity ratio with respect to theta is a maximum. This assures that the threshold intensity ratio is located in a region of the curve which is closest to a straight line. This reduces the effects of subsequent interpolation errors.

The threshold intensity ratio is calculated by the subroutine DERIV. Since the input intensity profile curve will have at least three maximum derivative points, DERIV calculates the average of the three intensity ratios. This average is then passed to the calling program, EXPOSURE.

EXPOSURE searches the intensity ratios and compares them with the value of the threshold intensity ratio. This process corresponds to the Micron Eye addressing a pixel and comparing its voltage to the threshold voltage. If an intensity ratio is greater than the threshold value, the ratio is assigned a digital value of 1. If the intensity ratio is less than the threshold value, the ratio is assigned a digital value of 0.

The digitized data is then searched to find the theta locations at which the digital intensities change from 0 --> 1, or from 1 --> 0. The theta locations are averaged to produce a theta location which is very close to the threshold intensity. Because this averaging process is occuring in the regions of steepest slope, error is assumed to be minimized since the curve can be approximated as a straight line (refer to Figure 30 in Chapter 6).

EXPOSURE provides the user with the option of introducing error into the perfect data. The program prompts the user to input the desired error and calls the subroutine RANDOM. RANDOM introduces random error into the intensity ratios and returns the imperfect data to EXPOSURE. EXPOSURE digitizes the imperfect data and searches for the occurences where 0-->1 and 1-->0. Imperfect data will have many more occurences of the digital intensities changing from 1-->0 and 0-->1. EXPOSURE will average the theta locations if they are in the same location (i.e., within ±.005 radians). This method has been tested for random error up to 5 percent.

```
$JOB
C          DATAMAKR.
C          THIS PROGRAM IS DESIGNED TO PRODUCE DATA FOR USE
C          BY THE SIMULATION PROGRAM "DIAFIND".
C          USER MUST EDIT PROGRAM TO CHANGE THE VALUE OF 'L'
C          AND THE INCREMENT VALUE FOR THETA.
C
      INTEGER I,N,M,K
      REAL DIAM, LAMBDA, L, KNOT, CONST, PI, D, X, J, DIA, T, B
      DIMENSION J(100), Y(100), R(100), S(100),
     & IERY(100), IERJ(100), DENOM(100),
     & T(200), C(100, 200), RC(100,200), SC(100,200), RSUM(200),
     & SSUM(200), EYE(200)
C       INPUT:
C                 DIAMETER IS THE DIAMETER OF THE FIBER.
C       LAMBDA IS THE WAVELENGTH OF THE
C       LASER.    L IS THE DISTANCE OF THE SAMPLE FIBER FROM THE
C       DIFFRACTION PATTERN.  ALL LENGTHS ARE IN METERS.
C
C
      CALL FRTCMS('CLRSCRN ')
      WRITE(6, 3)
    3 FORMAT('1', ' ')
      WRITE(6, 4)
    4 FORMAT(/,1X,'INPUT DIAMETER OF FIBER IN MICRONS ...')
      READ, DIA
C
C       B IS THE STARTING POINT OF THE THETA VALUES
      WRITE(6,10)
   10 FORMAT(/,1X,'INPUT STARTING POINT OF DATA (RADS)...')
      READ, B
C
C
      DIAM = DIA * (1D-06)
C
      PI = 3.141592654
      LAMBDA = 632.800D-09
      L = .030
C     D IS THE ACCURACY PARAMETER FOR THE BESJ SUBROUTINE:
      D = .000001
C
      M = 50
      K = 100
C
      X = (PI * DIAM) / LAMBDA
      KNOT = (2.0D0 * PI) / LAMBDA
      CONST = 2.0D0 / (KNOT * L * PI)
C
```

```
C
C
      WRITE(6, 5) M
    5 FORMAT(/,5X,'PROGRAM WILL CALCULATE N =',I3,4X,'BESSEL
     &COEFFICIENTS'/)
C
C
C*********************************************************************
C
C  CREATE DATA FILE IN WHICH TO PUT RESULTS
C
      CALL FRTCMS('FILEDEF ','08       ','DISK    ','BESTDAT ','DATA    '
     *,'A1      ')
C
C*********************************************************************
C
C
C       GENERATE THE REQUIRED BESSEL FUNCTION VALUES
C
C
C
      DO 100 I=1,M
      N = I-1
      IER = 0
C
      CALL BESJ(X,N,BJ,D,IER)
      J(I) = BJ
      IERJ(I) =  IER
      IER = 0
C
      CALL BESY(X,N,BY,IER)
      Y(I) = BY
      IERY(I) = IER
C
  100 CONTINUE
C
C*********************************************************************
C
C     GENERATE THE REQUIRED VALUES FOR THETA, SIMILAR TO THOSE
C     IN THE ACTUAL EXPERIMENT.
C     USER MUST INSERT THE DESIRED INCREMENT OF THETA (FOUR LINES
C     BELOW AS IN:  T(I) = ( I * INCREMENT ) + B  ).
C
      DO 200 I=1, K
      T(I) = ( I * .0025) + B
  200 CONTINUE
C
C*********************************************************************
C
```

```
C     CALCULATE THE R(N) AND  S(N)
C
C
C
      DO 300 I=1, M
      DENOM( I )  = ( J( I ) **2 +  Y( I ) **2 )
      R( I ) = ( J( I ) **2 ) / DENOM( I )
      S( I ) = ( J( I ) * Y( I ) ) / DENOM( I )
C
  300 CONTINUE
C
C*******************************************************************
C
C      CALCULATE THE MATRIX OF COSINE VALUES .......
C
C
C
       DO 400 I=2, M
       DO 399 N=1, K
C
          C( I-1, N)  =  COS ( ( I-1) * T(N)  )
C
 399   CONTINUE
 400   CONTINUE
C
C*******************************************************************
C
C          GENERATE THE MATRIX OF PRODUCTS
C
C
C
       DO 500 I=2, M
          DO 499 N=1, K
C
          RC( I-1, N )  =  R( I ) *  C( I-1, N )
C
          SC( I-1, N )  =  S( I ) *  C( I-1, N )
C
 499      CONTINUE
 500    CONTINUE
C
C*******************************************************************
C
C           SUM THE COLUMNS IN THE PRODUCT MATRICES .....
C
C
C
      DO 600 N=1, K
        RSUM( N ) = 0
        SSUM( N ) = 0
        DO 599 I=2, M
```

```
C
       RSUM(N) = RSUM(N) + RC( I-1, N )
       SSUM(N) = SSUM(N) + SC( I-1, N )
C
  599  CONTINUE
  600  CONTINUE
C
C*******************************************************************
C
C     FINAL CALCULATION ......
C
C
       DO 700 N=1, K
C
      EYE(N)=CONST*( ( R(1)+2*RSUM(N) )**2 + ( S(1)+2*SSUM(N) )**2)
C
 700   CONTINUE
C
C******************************************************************
C******************************************************************
C
C                          OUTPUT MODULE ....
C
      PRINT 1
  1   FORMAT ('1')
C
C
       PRINT 1
       PRINT,'FOR',M,'BESSEL COEFFICIENTS & DIAMETER OF',DIA,'MICRONS'
C
       DO 801 N=1, K
       WRITE(8,800) T(N), EYE(N)
 800   FORMAT(1X, E17.10, 1X, E17.10)
 801   CONTINUE
C
C
      STOP
      END
C
C*******************************************************************
C*******************************************************************
C
C
C         SUBROUTINES FOR CALCULATION OF THE BESSEL FUNCTIONS.
C
C
C        SUBROUTINE BESJ
C
```

```
C        PURPOSE
C           COMPUTE THE J BESSEL FUNCTION FOR A GIVEN ARGUMENT AND ORDER
C
C        USAGE
C           CALL BESJ(X,N,BJ,D,IER)
C
C        DESCRIPTION OF PARAMETERS
C           X  -THE ARGUMENT OF THE J BESSEL FUNCTION DESIRED
C           N  -THE ORDER OF THE J BESSEL FUNCTION DESIRED
C           BJ -THE RESULTANT J BESSEL FUNCTION
C           D  -REQUIRED ACCURACY
C           IER-RESULTANT ERROR CODE WHERE
C              IER=0  NO ERROR
C              IER=1  N IS NEGATIVE
C              IER=2  X IS NEGATIVE OR ZERO
C              IER=3  REQUIRED ACCURACY NOT OBTAINED
C              IER=4  RANGE OF N COMPARED TO X NOT CORRECT (SEE REMARKS)
C
C        REMARKS
C           N MUST BE GREATER THAN OR EQUAL TO ZERO, BUT IT MUST BE
C           LESS THAN
C              20+10*X-X** 2/3   FOR X LESS THAN OR EQUAL TO 15
C              90+X/2            FOR X GREATER THAN 15
C
C        SUBROUTINES AND FUNCTION SUBPROGRAMS REQUIRED
C           NONE
C
C        METHOD
C           RECURRENCE RELATION TECHNIQUE DESCRIBED BY H. GOLDSTEIN AND
C           R.M. THALER,'RECURRENCE TECHNIQUES FOR THE CALCULATION OF
C           BESSEL FUNCTIONS',M.T.A.C.,V.13,PP.102-108 AND I.A. STEGUN
C           AND M. ABRAMOWITZ,'GENERATION OF BESSEL FUNCTIONS ON HIGH
C           SPEED COMPUTERS',M.T.A.C.,V.11,1957,PP.255-257
C
C     ..................................................................
C
      SUBROUTINE BESJ(X,N,BJ,D,IER)
C
      BJ=.0
      IF(N)10,20,20
   10 IER=1
      RETURN
   20 IF(X)30,30,31
   30 IER=2
      RETURN
   31 IF(X-15.)32,32,34
   32 NTEST=20.+10.*X-X** 2/3
      GO TO 36
```

```
   34 NTEST=90.+X/2.
   36 IF(N-NTEST)40,38,38
   38 IER=4
      RETURN
   40 IER=0
      N1=N+1
      BPREV=.0
C
C     COMPUTE STARTING VALUE OF M
C
      IF(X-5.)50,60,60
   50 MA=X+6.
      GO TO 70
   60 MA=1.4*X+60./X
   70 MB=N+IFIX(X)/4+2
      MZERO=MAX0(MA,MB)
C
C     SET UPPER LIMIT OF M
C
      MMAX=NTEST
  100 DO 190 M=MZERO,MMAX,3
C
C     SET F(M),F(M-1)
C
      FM1=1.0E-28
      FM=.0
      ALPHA=.0
      IF(M-(M/2)*2)120,110,120
  110 JT=-1
      GO TO 130
  120 JT=1
  130 M2=M-2
      DO 160 K=1,M2
      MK=M-K
      BMK=2.*FLOAT(MK)*FM1/X-FM
      FM=FM1
      FM1=BMK
      IF(MK-N-1)150,140,150
  140 BJ=BMK
  150 JT=-JT
      S=1+JT
  160 ALPHA=ALPHA+BMK*S
      BMK=2.*FM1/X-FM
      IF(N)180,170,180
  170 BJ=BMK
  180 ALPHA=ALPHA+BMK
      BJ=BJ/ALPHA
      IF(ABS(BJ-BPREV)-ABS(D*BJ))200,200,190
```

```
  190 BPREV=BJ
      IER=3
  200 RETURN
      END
C
C     ..................................................................
C
C        SUBROUTINE BESY
C
C        PURPOSE
C           COMPUTE THE Y BESSEL FUNCTION FOR A GIVEN ARGUMENT AND ORDER
C
C        USAGE
C           CALL BESY(X,N,BY,IER)
C
C        DESCRIPTION OF PARAMETERS
C           X  -THE ARGUMENT OF THE Y BESSEL FUNCTION DESIRED
C           N  -THE ORDER OF THE Y BESSEL FUNCTION DESIRED
C           BY -THE RESULTANT Y BESSEL FUNCTION
C           IER-RESULTANT ERROR CODE WHERE
C              IER=0  NO ERROR
C              IER=1  N IS NEGATIVE
C              IER=2  X IS NEGATIVE OR ZERO
C              IER=3  BY HAS EXCEEDED MAGNITUDE OF 10**70
C
C        REMARKS
C           VERY SMALL VALUES OF X MAY CAUSE THE RANGE OF THE LIBRARY
C           FUNCTION ALOG TO BE EXCEEDED
C           X MUST BE GREATER THAN ZERO
C           N MUST BE GREATER THAN OR EQUAL TO ZERO
C
C        SUBROUTINES AND FUNCTION SUBPROGRAMS REQUIRED
C           NONE
C
C        METHOD
C           RECURRENCE RELATION AND POLYNOMIAL APPROXIMATION TECHNIQUE
C           AS DESCRIBED BY A.J.M.HITCHCOCK,'POLYNOMIAL APPROXIMATIONS
C           TO BESSEL FUNCTIONS OF ORDER ZERO AND ONE AND TO RELATED
C           FUNCTIONS', M.T.A.C., V.11,1957,PP.86-88, AND G.N. WATSON,
C           'A TREATISE ON THE THEORY OF BESSEL FUNCTIONS', CAMBRIDGE
C           UNIVERSITY PRESS, 1958, P. 62
C
C     ..................................................................
C
      SUBROUTINE BESY(X,N,BY,IER)
C
C     CHECK FOR ERRORS IN N AND X
C
```

```
      IF(N)180,10,10
   10 IER=0
      IF(X)190,190,20
C
C     BRANCH IF X LESS THAN OR EQUAL 4
C
   20 IF(X-4.0)40,40,30
C
C       COMPUTE YO AND Y1 FOR X GREATER THAN 4
C
   30 T1=4.0/X
      T2=T1*T1
      P0=((((-.0000037043*T2+.0000173565)*T2-.0000487613)*T2
     1  +.00017343)*T2-.001753062)*T2+.3989423
      Q0=((((.0000032312*T2-.0000142078)*T2+.0000342468)*T2
     1  -.0000869791)*T2+.0004564324)*T2-.01246694
      P1=((((.0000042414*T2-.0000200920)*T2+.0000580759)*T2
     1  -.000223203)*T2+.002921826)*T2+.3989423
      Q1=((((-.0000036594*T2+.00001622)*T2-.0000398708)*T2
     1  +.0001064741)*T2-.0006390400)*T2+.03740084
      A=2.0/SQRT(X)
      B=A*T1
      C=X-.7853982
      YO=A*P0*SIN(C)+B*Q0*COS(C)
      Y1=-A*P1*COS(C)+B*Q1*SIN(C)
      GO TO 90
C
C       COMPUTE YO AND Y1 FOR X LESS THAN OR EQUAL TO 4
C
   40 XX=X/2.
      X2=XX*XX
      T=ALOG(XX)+.5772157
      SUM=0.
      TERM=T
      YO=T
      DO 70 L=1,15
      IF(L-1)50,60,50
   50 SUM=SUM+1./FLOAT(L-1)
   60 FL=L
      TS=T-SUM
      TERM=(TERM*(-X2)/FL**2)*(1.-1./(FL*TS))
   70 YO=YO+TERM
      TERM = XX*(T-.5)
      SUM=0.
      Y1=TERM
      DO 80 L=2,16
      SUM=SUM+1./FLOAT(L-1)
      FL=L
```

```
      FL1=FL-1.
      TS=T-SUM
      TERM=(TERM*(-X2)/(FL1*FL))*((TS-.5/FL)/(TS+.5/FL1))
   80 Y1=Y1+TERM
      PI2=.6366198
      YO=PI2*YO
      Y1=-PI2/X+PI2*Y1
C
C     CHECK IF ONLY YO OR Y1 IS DESIRED
C
   90 IF(N-1)100,100,130
C
C     RETURN EITHER YO OR Y1 AS REQUIRED
C
  100 IF(N)110,120,110
  110 BY=Y1
      GO TO 170
  120 BY=YO
      GO TO 170
C
C    PERFORM RECURRENCE OPERATIONS TO FIND YN(X)
C
  130 YA=YO
      YB=Y1
      K=1
  140 T=FLOAT(2*K)/X
      YC=T*YB-YA
      IF(ABS(YC)-1.0E70)145,145,141
  141 IER=3
      RETURN
  145 K=K+1
      IF(K-N)150,160,150
  150 YA=YB
      YB=YC
      GO TO 140
  160 BY=YC
  170 RETURN
  180 IER=1
      RETURN
  190 IER=2
      RETURN
      END
C
C
$ENTRY
```

```
$JOB
C     DIAFIND.     THIS PROGRAM ACCEPTS THETA AND INTENSITY RATIO
C     DATA AND PROCEEDS TO FIND THE DIAMETER CORRESPONDING TO THE
C     DATA.   USER IS PROMPTED FOR THE INITIAL GUESS OF THE DIAMETER
C     WHICH MUST BE CLOSE TO THE ACTUAL DIAMETER OR THE PROGRAM MAY
C     FIND THE WRONG DIAMETER.   USER MUST MODIFY PROGRAM PRIOR TO
C     RUNNING:  K, L, AND M.    K IS THE NUMBER OF DATA POINTS TO BE
C     READ.   L IS THE SCREEN TO FIBER DISTANCE IN METERS.   M IS
C     THE NUMBER OF BESSEL TERMS TO BE COMPUTED.  (USUALLY 50, BUT
C     MAY NEED TO BE SMALLER IF CALCULATING SMALL DIAMETERS,
C     I.E. LESS THAN 5 MICRONS.)
C
C
C
      INTEGER I, COUNT, FLAG, LOWER, UPPER, K, M, NEWDEL
      REAL T, DELTAD, BETA, R, DEE, DIA, TEST
      REAL INTGES, INTACT, L, ACTUAL
      DIMENSION DEE(100), R(100), T(100), Q(100)
      DIMENSION INTACT(100), INTGES(100)
C
C       M IS THE NUMBER OF BESSEL TERMS TO BE COMPUTED
      M = 50
C       K IS THE NUMBER OF DATA POINTS INPUT TO THE PROGRAM
      K = 3
C       L IS THE SCREEN TO FIBER DISTANCE IN METERS
      L = .030
C
      DO 19 I=1, K
      READ(5, 18) T(I), INTACT(I)
 18   FORMAT(1X,E17.10, 1X,E17.10)
 19   CONTINUE
C
      PRINT 1
  1   FORMAT('1')
C
      DO 95 I=1, K
      PRINT,  T(I), INTACT(I)
 95   CONTINUE
C
C      THE RESULTS ARE OUTPUT TO THE FOLLOWING DATA FILE
C
      CALL FRTCMS('FILEDEF ','08      ','DISK    ','RESDAT  ','DATA    '
     *,'A1      ')
C
C
C
C            PROMPT USER FOR INPUT INITIAL GUESS DIAMETER:
C
```

```
 11   CALL FRTCMS('CLRSCRN ')
      WRITE(6, 12)
 12   FORMAT('1', ' ')
      WRITE(6, 14)
 14   FORMAT('/',1X,'INPUT INITIAL GUESS DIAMETER, IN MICRONS .....')
      READ, DIA
C
      WRITE(6, 15)
 15   FORMAT(1X,'INPUT ACTUAL DIAMETER ASSOCIATED WITH DATA (IN
     &MICRONS).....')
      READ, ACTUAL
C
      DIA = DIA * (1D-06)
      DEE(1) = DIA
C
C           ECHO INPUT  TO THE SCREEN:
C
      CALL FRTCMS('CLRSCRN ')
      WRITE(6, 16) DEE(1)
 16   FORMAT('/',1X,'INITIAL GUESS DIAMETER INPUT,IN METERS IS',E12.5)
C
C
      WRITE(6, 17) L
 17   FORMAT('/',1X,'SCREEN TO FIBER DISTANCE IS ',E12.5,' METERS ')
C
C
      RR = 0.0
      DELTAD = .05E-06
      BETA = 1E-20
C
C
C
      D = DEE(1)
      CALL RESID(D, RR, INTACT, INTGES, K, M, T, L)
      R(1) = RR
C
C
      NEWDEL = 0
      COUNT = 1
      I=1
      FLAG = 1
      LOWER = 0
      UPPER = 0
      TEST = 99
C
      PRINT, ' '
      PRINT, ' I    RESID       DIAMETER       DELTAD         TEST'
      PRINT, ' '
```

```
C
 30   WHILE( ABS(TEST) .GT. BETA) DO
C
C
 31   IF(FLAG .EQ. 1) THEN
C
            DEE( I+1) = DEE(1) + I * DELTAD
            D = DEE( I+1)
C
            CALL RESID(D, RR, INTACT, INTGES, K, M, T, L)
C
            R( I+1) = RR
            UPPER = UPPER + 1
      END IF
C
C
C
C
 32   IF(FLAG .EQ. 0) THEN
C
            DEE( I+1) = DEE(1) - I * DELTAD
            D = DEE( I+1)
C
            CALL RESID(D, RR, INTACT, INTGES, K, M, T, L)
C
            R( I+1) = RR
            LOWER = LOWER + 1
      END IF
C
C
C
      IF(LOWER .EQ. 1) THEN
C
            TEST = R( I+1) - R( I-1)
      ELSE
            TEST = R( I+1) - R( I)
      END IF
C
      PRINT 62, I, R( I), DEE( I), DELTAD, TEST
 62   FORMAT(' ',1X,I2,1X,E11.4,1X,E12.5,1X,E12.5,1X,E13.5)
C
C
      IF( TEST ) 34, 33, 35
C
C
C
 33    GO TO 35
C
```

```
C
 34     IF(LOWER .EQ. 0) THEN
C
                FLAG = 1
        ELSE
                FLAG = 0
        END IF
        GOTO 36
C
C
 35     IF(COUNT .EQ. 1) THEN
C
                FLAG = 0
C
C
        ELSEIF(DELTAD .EQ. .05E-06) THEN
              DELTAD = .01E-06
              NEWDEL = 1
              GOTO 38
C
        ELSEIF(DELTAD .EQ. .01E-06) THEN
              DELTAD = .005E-06
              NEWDEL = 1
              GOTO 38
C
C
        ELSEIF(DELTAD .EQ. .005E-06) THEN
              DELTAD = .001E-06
              NEWDEL = 1
              GOTO 38
C
        ELSEIF(DELTAD .EQ. .001E-06)THEN
                QUIT 2
C
        END IF
C
C
 36     I = I + 1
 38     COUNT = COUNT + 1
C
        IF( (NEWDEL .EQ. 1) .AND. (I .GE. 2)) THEN
                DEE(1) = DEE(I-1)
                  R(1) = R(I-1)
                     I = 1
              NEWDEL   = 0
        END IF
C
C
```

```
C
      IF( (NEWDEL .EQ. 1) .AND. (I .EQ. 1)) THEN
               I = 1
         NEWDEL = 0
      END IF
C
      IF(COUNT .GE. 50) GOTO 40
C
      END WHILE
C
      PRINT, ' '
C
C
C
C**********************************************************************
C**********************************************************************
C
C                          OUTPUT MODULE
C
C
      PRINT, 'FOR K = ',K
      PRINT, ' '
      PRINT 50, TEST, BETA
50    FORMAT(' ', 'TEST =',E12.5, ' BETA = ', E12.5)
      PRINT, ' '
      PRINT 51, R(I)
51    FORMAT(' ', 'THE RESIDUAL IS =', E12.5)
      PRINT, ' '
      PRINT 52, DEE(I)
52    FORMAT(' ', ' THE PROGRAM CALCULATES THE DIAMETER =',E12.5)
      PRINT, ' '
      PRINT, 'THE ACTUAL DIAMETER IS', ACTUAL
      PRINT 53, DIA
53    FORMAT(' ', ' THE INITIAL GUESS DIAMETER WAS = ', E12.5)
      PRINT, ' '
      PRINT, ' TOTAL ITERATIONS = ', COUNT
      PRINT, ' '
      GOTO 999
C
C37   PRINT, ' TEST IS EQUAL TO ZERO, D(GUESS) = ACTUAL D'
C     GOTO 999
C
40    PRINT, 'COUNT .GE. 50, USING TOO MANY ITERATIONS'
      PRINT, 'TOTAL ITERATIONS AT INTERRUPTION=', COUNT
C
C
999   CONTINUE
C
C       THIS WRITE STATEMENT WRITES THE RESULTS TO THE FILE
```

```
C       NAMED "RESDAT LISTING A1".
C
        WRITE(8,57) TEST, BETA, R(I),ACTUAL,DIA, DEE(I), COUNT, DELTAD
       &, M, K, T(1), T(K), R(I+1), DEE(I+1)
 57     FORMAT( / ,1X, 'TEST = ', E17.10,//,1X, ' BETA =', E17.10,//,1X,
       &'RESIDUAL = ', E17.10,//, 1X,'ACTUAL DIAMETER =', E17.10, //,1X,
       &'INITIAL GUESS DIAMETER = ', E17.10, //,1X,
       &'CALCULATED DIAMETER =', E17.10,//,1X,'ITERATIONS = ', I3, //,
       & 1X, 'FINAL DELTA D = ', E17.10,//,1X, '# BESSEL TERMS = ', I2,
       & //,1X,'# VALUES OF THETA = ', I3,//, 1X,'THETA RANGES FROM ',
       & E11.4,' TO ',E11.4,' RADIANS'
       & ,//,' R(I+1) = ',1X,E17.10, ' DEE(I+1) = ',1X,E17.10)
C
C
        STOP
        END
C
C
C*****************************************************************
C*****************************************************************
C
C
C                      PROGRAM SUBROUTINES
C
C       THE SUBROUTINE  USED BELOW IS  CALLED RESID.
C       RESID CALLS BESJ AND BESY.   BESJ AND BESY ARE NONIMSL
C       LIBRARY ROUTINES (SINGLE PRECISION) WHICH CALCULATE THE
C       VALUES OF THE BESSEL FUNCTIONS.  THESE FUNCTIONS ARE USED TO
C       TO FIND THE VALUES OF THE INTENSITY RATIOS.  TWO INTENSITY RATIOS
C       ARE THEN USED TO GIVE A RESIDUAL WHICH IS THE VALUE RETURNED BY
C       THE ROUTINE RESID.
C
C
C
C
C          THIS PROGRAM IS USED TO CALCULATE THE RESIDUAL CURVE POINTS
C          FOR SPECIFIED DIAMETERS.
C
        SUBROUTINE RESID(D, RR, INTACT, INTGES, K, M, T, L)
C
C
C          D     IS THE DIAMETER PASSED TO SUBROUTINE
C          Q     IS A FLAG DICTATING COMPUTATION OF THE ACTUAL DIAMETER
C                     INTENSITIES, OR THE GUESS DIAMETER INTENSITIES
C         RR     IS THE RESIDUAL VALUE PASSED BACK TO CALLING ROUTINE
C        INTGES IS A 100 X 1 ARRAY CONTAINING INTENSITY VALUESFOR D,GUESS
C        INTACT IS A 100 X 1 ARRAY CONTAINING INTENSITY VALUES FOR D,ACTUAL
```

```
C       K     IS THE NUMBER OF THETA INCREMENTS TO BE CALCULATED/PASSED
C       M     IS THE NUMBER OF FIRST AND SECOND KIND BESSEL FUNCTIONS
C                TO BE CALCULATED
C       T     IS ARRAY OF THETA VALUES OF K INCREMENTS EVERY .002 RADS.
C       L     IS DISTANCE IN METERS FROM THE FIBER TO DIFF PATTERN
C
      INTEGER I,N,M,K
      REAL DIAM, LAMBDA, L, KNOT, CONST, PI, D, X, J, DIA, T
      REAL INTDIF, RR, DD, INTACT, INTGES
      DIMENSION J(100), Y(100), R(100), S(100),
     & IERY(100), IERJ(100), DENOM(100), DIST(100),
     & T(100), C(100, 100), RC(100,100), SC(100,100), RSUM(100),
     & SSUM(100), INTACT(100), INTDIF(100),INTGES(100)
C
C
      PI = 3.141592654
      LAMBDA = 632.800D-09
C             LAMBDA IS THE WAVELENGTH (METERS) OF THE LASER
C
C        DD IS THE ACCURACY PARAMETER FOR THE SUBROUTINE BESJ
C
      DD = .000001
C
C
      KNOT = (2.0D0 * PI) / LAMBDA
      CONST = 2.0D0 / (KNOT * L * PI)
C
C
C
C
      X = (PI * D) / LAMBDA
C
C   X IS THE VALUE OF ALPHA, THE DIAMTER DEPENDENT ARGUMENT FOR THE
C       BESSEL FUNCTIONS.
C
C       GENERATE THE REQUIRED BESSEL FUNCTION VALUES
C
C
C
C
      DO 100 I=1,M
      N = I-1
      IER = 0
C
      CALL BESJ(X,N,BJ,DD,IER)
      J(I) = BJ
      IERJ(I) =  IER
      IER = 0
C
```

```
      CALL BESY(X,N,BY,IER)
      Y(I) = BY
      IERY(I) = IER
C
  100 CONTINUE
C
C***********************************************************************
C
C     GENERATE THE REQUIRED VALUES FOR THETA, SIMILAR TO THOSE
C     IN THE ACTUAL EXPERIMENT, WHERE THETA=ARCTAN(DIST/L).
C     HERE, DISTANCE IS EVERY TWO MILLIMETERS FROM CENTER, AND
C     L IS THE SCREEN TO LATH DISTANCE, WHICH IS .5636 METERS.
C
C
C
      DO 200 I=1, K
      T(I) = I*.002 + .05
  200 CONTINUE
C
C***********************************************************************
C
C     CALCULATE THE R(N) AND  S(N)
C
C
C
      DO 300 I=1, M
      DENOM(I)  = (  J(I) **2 +  Y(I) **2 )
      R(I) = (  J(I) **2 )  /  DENOM(I)
      S(I) = (  J(I) * Y(I) ) / DENOM(I)
C
  300 CONTINUE
C
C***********************************************************************
C
C      CALCULATE THE MATRIX OF COSINE VALUES .......
C
C
       DO 400 I=2, M
       DO 399 N=1, K
C
          C(I-1, N)  =  COS ( (I-1) * T(N)  )
C
  399  CONTINUE
  400  CONTINUE
C
C***********************************************************************
C
C         GENERATE THE MATRIX OF PRODUCTS
```

```
C
C
      DO 500 I=2, M
         DO 499 N=1, K
C
         RC( I-1, N )  =  R(I) *  C( I-1, N )
C
         SC( I-1, N )  =  S(I) *  C( I-1, N )
C
 499     CONTINUE
 500   CONTINUE
C
C*******************************************************************
C
C           SUM THE COLUMNS IN THE PRODUCT MATRICES .....
C
C
      DO 600 N=1, K
        RSUM(N) = 0
        SSUM(N) = 0
        DO 599 I=2, M
C
        RSUM(N) = RSUM(N) + RC( I-1, N )
        SSUM(N) = SSUM(N) + SC( I-1, N )
C
 599    CONTINUE
 600    CONTINUE
C
C*******************************************************************
C
C     FINAL CALCULATION ......
C
C
        DO 700 N=1, K
C
       INTGES(N)=CONST*((R(1)+2*RSUM(N))**2 + (S(1)+2*SSUM(N))**2)
C
 700    CONTINUE
 1000   CONTINUE
C
C*******************************************************************
C           RESIDUAL SUBROUTINE
C
C             THIS TEST SKIPS ROUTINE IF ONLY CALCULATING INTENSITIES
C             FOR THE ACTUAL DIAMETER:
C          INTACT(I) IS THE INTENSITY ARRAY FROM THE INPUT DATA FILE
C
C
```

```
C
      RR = 0.0
C
       DO 900 I=1, K
       INTDIF(I) = ( INTGES(I) - INTACT(I) )
       RR = RR + (INTDIF(I) **2)
  900  CONTINUE
C
C
 998  CONTINUE
      RETURN
      END
C
C**********************************************************************
C**********************************************************************
C
C**********************************************************************
C**********************************************************************
C
C                                                                      BESJ  10
C     .................................................................BESJ  20
C                                                                      BESJ  30
C        SUBROUTINE BESJ                                               BESJ  40
C                                                                      BESJ  50
C        PURPOSE                                                       BESJ  60
C           COMPUTE THE J BESSEL FUNCTION FOR A GIVEN ARGUMENT AND ORDERBESJ  70
C                                                                      BESJ  80
C        USAGE                                                         BESJ  90
C           CALL BESJ(X,N,BJ,D,IER)                                    BESJ 100
C                                                                      BESJ 110
C        DESCRIPTION OF PARAMETERS                                     BESJ 120
C           X  -THE ARGUMENT OF THE J BESSEL FUNCTION DESIRED          BESJ 130
C           N  -THE ORDER OF THE J BESSEL FUNCTION DESIRED             BESJ 140
C           BJ -THE RESULTANT J BESSEL FUNCTION                        BESJ 150
C           D  -REQUIRED ACCURACY                                      BESJ 160
C           IER-RESULTANT ERROR CODE WHERE                             BESJ 170
C              IER=0  NO ERROR                                         BESJ 180
C              IER=1  N IS NEGATIVE                                    BESJ 190
C              IER=2  X IS NEGATIVE OR ZERO                            BESJ 200
C              IER=3  REQUIRED ACCURACY NOT OBTAINED                   BESJ 210
C              IER=4  RANGE OF N COMPARED TO X NOT CORRECT (SEE REMARKS)BESJ 220
C                                                                      BESJ 230
C        REMARKS                                                       BESJ 240
C           N MUST BE GREATER THAN OR EQUAL TO ZERO, BUT IT MUST BE    BESJ 250
C           LESS THAN                                                  BESJ 260
C              20+10*X-X** 2/3   FOR X LESS THAN OR EQUAL TO 15        BESJ 270
C              90+X/2           FOR X GREATER THAN 15                  BESJ 280
C                                                                      BESJ 290
```

```
C
C        SUBROUTINES AND FUNCTION SUBPROGRAMS REQUIRED
C           NONE
C
C        METHOD
C           RECURRENCE RELATION TECHNIQUE DESCRIBED BY H. GOLDSTEIN AND
C           R.M. THALER,'RECURRENCE TECHNIQUES FOR THE CALCULATION OF
C           BESSEL FUNCTIONS',M.T.A.C.,V.13,PP.102-108 AND I.A. STEGUN
C           AND M. ABRAMOWITZ,'GENERATION OF BESSEL FUNCTIONS ON HIGH
C           SPEED COMPUTERS',M.T.A.C.,V.11,1957,PP.255-257
C
C     ..................................................................
C
      SUBROUTINE BESJ(X,N,BJ,D,IER)
C
      BJ=.0
      IF(N)10,20,20
   10 IER=1
      RETURN
   20 IF(X)30,30,31
   30 IER=2
      RETURN
   31 IF(X-15.)32,32,34
   32 NTEST=20.+10.*X-X** 2/3
      GO TO 36
   34 NTEST=90.+X/2.
   36 IF(N-NTEST)40,38,38
   38 IER=4
      RETURN
   40 IER=0
      N1=N+1
      BPREV=.0
C
C     COMPUTE STARTING VALUE OF M
C
      IF(X-5.)50,60,60
   50 MA=X+6.
      GO TO 70
   60 MA=1.4*X+60./X
   70 MB=N+IFIX(X)/4+2
      MZERO=MAXO(MA,MB)
C
C     SET UPPER LIMIT OF M
C
      MMAX=NTEST
  100 DO 190 M=MZERO,MMAX,3
C
C     SET F(M),F(M-1)
C
```

```
      FM1=1.0E-28                                                       BESJ 780
      FM=.0                                                             BESJ 790
      ALPHA=.0                                                          BESJ 800
      IF(M-(M/2)*2)120,110,120                                          BESJ 810
  110 JT=-1                                                             BESJ 820
      GO TO 130                                                         BESJ 830
  120 JT=1                                                              BESJ 840
  130 M2=M-2                                                            BESJ 850
      DO 160 K=1,M2                                                     BESJ 860
      MK=M-K                                                            BESJ 870
      BMK=2.*FLOAT(MK)*FM1/X-FM                                         BESJ 880
      FM=FM1                                                            BESJ 890
      FM1=BMK                                                           BESJ 900
      IF(MK-N-1)150,140,150                                             BESJ 910
  140 BJ=BMK                                                            BESJ 920
  150 JT=-JT                                                            BESJ 930
      S=1+JT                                                            BESJ 940
  160 ALPHA=ALPHA+BMK*S                                                 BESJ 950
      BMK=2.*FM1/X-FM                                                   BESJ 960
      IF(N)180,170,180                                                  BESJ 970
  170 BJ=BMK                                                            BESJ 980
  180 ALPHA=ALPHA+BMK                                                   BESJ 990
      BJ=BJ/ALPHA                                                       BESJ1000
      IF(ABS(BJ-BPREV)-ABS(D*BJ))200,200,190                            BESJ1010
  190 BPREV=BJ                                                          BESJ1020
      IER=3                                                             BESJ1030
  200 RETURN                                                            BESJ1040
      END                                                               BESJ1050
C                                                                       BESY  10
C     ..................................................................BESY  20
C                                                                       BESY  30
C        SUBROUTINE BESY                                                BESY  40
C                                                                       BESY  50
C        PURPOSE                                                        BESY  60
C           COMPUTE THE Y BESSEL FUNCTION FOR A GIVEN ARGUMENT AND ORDERBESY  70
C                                                                       BESY  80
C        USAGE                                                          BESY  90
C           CALL BESY(X,N,BY,IER)                                       BESY 100
C                                                                       BESY 110
C        DESCRIPTION OF PARAMETERS                                      BESY 120
C           X  -THE ARGUMENT OF THE Y BESSEL FUNCTION DESIRED           BESY 130
C           N  -THE ORDER OF THE Y BESSEL FUNCTION DESIRED              BESY 140
C           BY -THE RESULTANT Y BESSEL FUNCTION                         BESY 150
C           IER-RESULTANT ERROR CODE WHERE                              BESY 160
C              IER=0  NO ERROR                                          BESY 170
C              IER=1  N IS NEGATIVE                                     BESY 180
C              IER=2  X IS NEGATIVE OR ZERO                             BESY 190
C              IER=3  BY HAS EXCEEDED MAGNITUDE OF 10**70               BESY 200
```

```
C
C     REMARKS
C        VERY SMALL VALUES OF X MAY CAUSE THE RANGE OF THE LIBRARY
C        FUNCTION ALOG TO BE EXCEEDED
C        X MUST BE GREATER THAN ZERO
C        N MUST BE GREATER THAN OR EQUAL TO ZERO
C
C     SUBROUTINES AND FUNCTION SUBPROGRAMS REQUIRED.
C        NONE
C
C     METHOD
C        RECURRENCE RELATION AND POLYNOMIAL APPROXIMATION TECHNIQUE
C        AS DESCRIBED BY A.J.M.HITCHCOCK,'POLYNOMIAL APPROXIMATIONS
C        TO BESSEL FUNCTIONS OF ORDER ZERO AND ONE AND TO RELATED
C        FUNCTIONS', M.T.A.C., V.11,1957,PP.86-88, AND G.N. WATSON,
C        'A TREATISE ON THE THEORY OF BESSEL FUNCTIONS', CAMBRIDGE
C        UNIVERSITY PRESS, 1958, P. 62
C
C     ..................................................................
C
      SUBROUTINE BESY(X,N,BY,IER)
C
C     CHECK FOR ERRORS IN N AND X
C
      IF(N)180,10,10
   10 IER=0
      IF(X)190,190,20
C
C     BRANCH IF X LESS THAN OR EQUAL 4
C
   20 IF(X-4.0)40,40,30
C
C       COMPUTE Y0 AND Y1 FOR X GREATER THAN 4
C
   30 T1=4.0/X
      T2=T1*T1
      P0=((((-.0000037043*T2+.0000173565)*T2-.0000487613)*T2
     1  +.00017343)*T2-.001753062)*T2+.3989423
      Q0=((((.0000032312*T2-.0000142078)*T2+.0000342468)*T2
     1  -.0000869791)*T2+.0004564324)*T2-.01246694
      P1=((((.0000042414*T2-.0000200920)*T2+.0000580759)*T2
     1  -.000223203)*T2+.002921826)*T2+.3989423
      Q1=((((-.0000036594*T2+.00001622)*T2-.0000398708)*T2
     1  +.0001064741)*T2-.0006390400)*T2+.03740084
      A=2.0/SQRT(X)
      B=A*T1
      C=X-.7853982
      Y0=A*P0*SIN(C)+B*Q0*COS(C)
```

```
      Y1=-A*P1*COS(C)+B*Q1*SIN(C)                                   BESY 690
      GO TO 90                                                      BESY 700
C                                                                   BESY 710
C       COMPUTE Y0 AND Y1 FOR X LESS THAN OR EQUAL TO 4             BESY 720
C                                                                   BESY 730
   40 XX=X/2.                                                       BESY 740
      X2=XX*XX                                                      BESY 750
      T=ALOG(XX)+.5772157                                           BESY 760
      SUM=0.                                                        BESY 770
      TERM=T                                                        BESY 780
      Y0=T                                                          BESY 790
      DO 70 L=1,15                                                  BESY 800
      IF(L-1)50,60,50                                               BESY 810
   50 SUM=SUM+1./FLOAT(L-1)                                         BESY 820
   60 FL=L                                                          BESY 830
      TS=T-SUM                                                      BESY 840
      TERM=(TERM*(-X2)/FL**2)*(1.-1./(FL*TS))                       BESY 850
   70 Y0=Y0+TERM                                                    BESY 860
      TERM = XX*(T-.5)                                              BESY 870
      SUM=0.                                                        BESY 880
      Y1=TERM                                                       BESY 890
      DO 80 L=2,16                                                  BESY 900
      SUM=SUM+1./FLOAT(L-1)                                         BESY 910
      FL=L                                                          BESY 920
      FL1=FL-1.                                                     BESY 930
      TS=T-SUM                                                      BESY 940
      TERM=(TERM*(-X2)/(FL1*FL))*((TS-.5/FL)/(TS+.5/FL1))           BESY 950
   80 Y1=Y1+TERM                                                    BESY 960
      PI2=.6366198                                                  BESY 970
      Y0=PI2*Y0                                                     BESY 980
      Y1=-PI2/X+PI2*Y1                                              BESY 990
C                                                                   BESY1000
C     CHECK IF ONLY Y0 OR Y1 IS DESIRED                             BESY1010
C                                                                   BESY1020
   90 IF(N-1)100,100,130                                            BESY1030
C                                                                   BESY1040
C     RETURN EITHER Y0 OR Y1 AS REQUIRED                            BESY1050
C                                                                   BESY1060
  100 IF(N)110,120,110                                              BESY1070
  110 BY=Y1                                                         BESY1080
      GO TO 170                                                     BESY1090
  120 BY=Y0                                                         BESY1100
      GO TO 170                                                     BESY1110
C                                                                   BESY1120
C    PERFORM RECURRENCE OPERATIONS TO FIND YN(X)                    BESY1130
C                                                                   BESY1140
  130 YA=Y0                                                         BESY1150
      YB=Y1                                                         BESY1160
```

```
      K=1                                                               BESY1170
  140 T=FLOAT(2*K)/X                                                    BESY1180
      YC=T*YB-YA                                                        BESY1190
      IF(ABS(YC)-1.0E70)145,145,141                                     BESY1200
  141 IER=3                                                             BESY1210
      RETURN                                                            BESY1220
  145 K=K+1                                                             BESY1230
      IF(K-N)150,160,150                                                BESY1240
  150 YA=YB                                                             BESY1250
      YB=YC                                                             BESY1260
      GO TO 140                                                         BESY1270
  160 BY=YC                                                             BESY1280
  170 RETURN                                                            BESY1290
  180 IER=1                                                             BESY1300
      RETURN                                                            BESY1310
  190 IER=2                                                             BESY1320
      RETURN                                                            BESY1330
      END                                                               BESY1340
$ENTRY
```

```
$JOB
C     EXPOSURE.    THIS PROGRAM TAKES AN EXPOSURE OF INTENSITY
C     RATIOS VERSUS THETA DATA.  IT BEGINS BY RECOMMENDING THE
C     OPTIMUM EXPOSURE BY FINDING THE MAXIMUM DERIVATIVES OF THE
C     INTENSITY RATIO VS THETA CURVES.  THE INTENSITY RATIOS
C     CORRESPONDING TO THE MAXIMUM DERIVATIVES ARE AVERAGED AND
C     RECOMMENDED AS A GOOD STARTING POINT FOR EXPOSURE.
C
C     THE PROGRAM CALLS THE ATTACHED SUBROUTINES 'DERIV' AND
C     'RANDOM'.   DERIV CALCULATES THE OPTIMUM EXPOSURE AND
C     RANDOM INTRODUCES RANDOM ERROR INTO THE INTENSITY RATIO
C     DATA.
C
C     VARIABLE DEFINITIONS:
C
C      INT      ARRAY OF INTENSITY RATIOS (INPUT ARRAY)
C        T      ARRAY OF THETA LOCATIONS (INPUT ARRAY)
C     DIGINT    ARRAY OF DIGITIZED INTENSITY VALUES
C     DESINT    DESIRED INTENSITY RATIO (EXPOSURE VALUE)
C               THE 'INT' ARRAY IS DIGITIZED WITH RESPECT TO
C               THE VALUE OF 'DESINT'
C
C     INTAVG    THE AVERAGE VALUE OF THE MAX DERIVATIVE INTENSITIES
C               'INTAVG' IS RETURNED FROM THE SUBROUTINE 'SLOPE'
C
C     THLOC     ARRAY OF THETA LOCATIONS CORRESPONDING TO THE PROGRAM
C               LOCATED INTENSITY RATIOS.  (I.E. DESINT)
C
C     ERR       VALUE OF ERROR TO BE INTRODUCED IN THE RANDOM
C               SUBROUTINE. EXAMPLE: 1% ERROR INPUT AS .01.
C
C    INTERR     ARRAY OF INTENSITY RATIOS RETURNED FROM THE SUBROUTINE
C               RANDOM.
C
C    GUDINT     GOOD INTENSITY RATIOS
C
C
C     FLAG      SEARCH FLAG USED DURING DIGITIZATION
C     EFLAG     FLAG TO INDICATE IF ERROR HAS BEEN INTRODUCED INTO DATA
C     ERROR     FLAG INDICATING USER DESIRE TO CALL 'RANDOM' SUBROUTINE
C     DEFALT    FLAG INDICATING USER DESIRE TO KEEP RECOMMENDED SEARCH
C               INTENSITY VALUE, OR SELECT ANOTHER.
C
C
          INTEGER DIGINT, FLAG, EFLAG, ERROR, DEFALT, KNOW, IX
          INTEGER Z, M, SUM, LL, VG, FF, BB, KK, CC, RS
          REAL INT, T, NEWINT, THLOC, DESINT, INTAVG, ERR, INTB
          REAL INTERR, GUDINT, DIAMTR, ANYNUM, AA, TAVG, DIFF
```

```
      DIMENSION DIGINT(400), INT(400), NEWINT(400), TAVG(50)
      DIMENSION THLOC(400), INTERR(400), GUDINT(400), T(400)
      DIMENSION AVG(50)
      DIMENSION INTB(1200), TB(1200), RS(15)
C
C
      CALL FRTCMS('FILEDEF ','08      ','DISK    ','DIGITAL ','DATA    '
     *,'A1      ')
C
C
      CALL FRTCMS('FILEDEF ','09      ','DISK    ','EXP     ','WATFIV  '
     *,'A1      ')
C
C     'ERROR' IS NOT THE ERROR TO BE INTRODUCED.  IT IS A FLAG SO
C     THAT PROGRAM PROMPTS USER FOR ERROR ('ERR') IF 'ERROR' = 0.
C      K IS THE NUMBER OF DATA POINTS TO BE INPUT INTO THE PROGRAM.
       ERROR = 0
       K = 400
C
C     READ IN THE DATA FILE ......
C
       DO 10 I=1, 400
       READ(5,9) T(I), INT(I)
    9  FORMAT(1X,E17.10, 1X,E17.10)
   10  CONTINUE
C
C
       CALL FRTCMS('CLRSCRN ')
C
       WRITE(6,12)
   12 FORMAT(1X,'DO YOU KNOW THE DIAMETER ASSOCIATED WITH THIS
     &DATA?',/,1X, '1=YES,  0=NO',/)
      READ, KNOW
C
      IF(KNOW .EQ. 1) THEN
      WRITE(6,13)
   13 FORMAT(1X, 'INPUT THE DIAMETER ASSOCIATED WITH THIS DATA,
     &(IN MICRONS)')
      READ, DIAMTR
      ELSE
      DIAMTR = 0.000000000
      WRITE(6,14)
   14 FORMAT(1X, 'DIAMETER UNKNOWN, BUT NOT NECESSARY',/,1X,'TYPE
     &ANY NUMBER TO CONTINUE ......')
      READ, ANYNUM
      ENDIF
C
      KNOW = 1
```

```
C
      CALL SLOPE(T, INT, K, GUDINT, NO, DESINT, DIAMTR)
C
      CALL FRTCMS('CLRSCRN ')
C
      WRITE(6, 100) DESINT
 100  FORMAT(' ', 'BASED ON THE MAXIMUM INTENSITY DERIVATIVES, THE',
     &/,1X, 'SUBROUTINE SLOPE RECOMMENDS THE FOLLOWING INTENSITY',
     &/,1X, 'RATIO FOR AN OPTIMUM EXPOSURE:  ', E17.10, /,1X,
     &'THIS VALUE IS THE AVERAGE OF THE FOLLOWING INTENSITY RATIOS:')
C
      DO 110 I=1, NO
      WRITE(6, 109) GUDINT(I)
 109  FORMAT(1X,E17.10, /)
 110  CONTINUE
C
      WRITE(6, 120)
 120  FORMAT(1X,'DO YOU DESIRE TO SELECT ONE OF THE ABOVE INTENSITY
     &RATIOS?',/1X,' IF NOT, THE RECOMMENDED VALUE IS THE DEFAULT
     &VALUE.',/,1X,'  ENTER  1=YES,  0=NO')
      READ, DEFALT
C
      IF(DEFALT .EQ. 1) THEN
      WRITE(6, 130)
 130  FORMAT(' ',/, '  INPUT THE DESIRED INTENSITY VALUE')
      READ, DESINT
      END IF
C
      CALL FRTCMS('CLRSCRN ')
C
      EFLAG = 0
      WRITE(6, 140)
 140  FORMAT(/,1X,'DO YOU DESIRE TO SIMULATE ERROR? 1=YES, 0=NO')
      READ, ERROR
C
      IF(ERROR .EQ. 1)  THEN
      WRITE(6, 150)
 150  FORMAT(/,1X,'INPUT THE DESIRED ERROR (I.E. INPUT 1% AS .01)')
      READ, ERR
C
      WRITE(6,151)
 151  FORMAT(1X,'INPUT ODD INTEGER LESS THAN 99999 TO SEED GENERATOR')
      READ, IX
C
      CALL FRTCMS('CLRSCRN ')
C
      CALL RANDOM(T, INT, INTERR, ERR, K, DIAMTR, IX)
      EFLAG = 1
```

```
        END IF
C
C
        IF( EFLAG .EQ. 1) THEN
        DO 160 I=1, K
        INT( I ) = INTERR( I )
160     CONTINUE
        END IF
C
C
        DO 20 I=1, K
        IF (  INT( I )  .GE. DESINT ) THEN
        DIGINT( I ) = 0
        ELSE
        DIGINT( I ) = 1
        END IF
20      CONTINUE
C
C
        IF( DIGINT( 1) .EQ. 0) THEN
        FLAG = 0
        ELSE
        FLAG = 1
        END IF
C
C
        L = 1
        J = K-1
        DO 30 I=1, J
C
        IF( (FLAG .EQ. 0)  .AND.  (DIGINT( I ) .EQ. 0) ) GO TO 30
C
        IF( (FLAG .EQ. 1)  .AND.  (DIGINT( I ) .EQ. 1) ) GO TO 30
C
        IF( (FLAG .EQ. 0) .AND. (DIGINT( I ) .EQ. 1) ) THEN
C
        THLOC( L ) = (  T( I ) + T( I-1) ) / 2
            L = L + 1
            FLAG = 1
            GO TO 30
            END IF
C
         IF( (FLAG .EQ. 1) .AND. (DIGINT( I ) .EQ. 0) ) THEN
         THLOC( L ) = (  T( I ) + T( I-1) ) / 2
         L = L + 1
         FLAG = 0
         GO TO 30
         END IF
```

```
C
 30     CONTINUE
C
        IF(KNOW .EQ. 1) THEN
        WRITE(8, 35) DIAMTR
 35     FORMAT( 1X, 'FOR A DIAMETER = ',F8.5,' MICRONS',/)
        ELSE
        WRITE(8,36)
 36     FORMAT( 1X, ' DIAMETER UNKNOWN .......   ',/)
        END IF
C
        WRITE(8 ,38)
 38     FORMAT( 4X, 'THETA',10X,'INTENSITY',8X,'DIGITAL INTENSITY',/)
C
        DO 41 I=1, J
        WRITE(8,40)  T(I), INT(I), DIGINT(I)
 40     FORMAT( 1X,E17.10, 1X,E17.10, 1X,I2)
 41     CONTINUE
C
C
        WRITE(8, 45) DESINT
 45     FORMAT(//,'THE THETA LOCATIONS FOR THE DESIRED INTENSITY',
       &E17.10, ' ARE:  ', //)
C
C
        WRITE(8 ,47)
 47     FORMAT( 1X, 'THETA LOCATION', 4X,'DESIRED INTENSITY',/)
C
C
        M = L - 1
C
        DO 51 I=1, M
        WRITE(8,50)  THLOC(I), DESINT
 50     FORMAT( 1X,E17.10, 1X,E17.10)
 51     CONTINUE
C
C
C          THE FOLLOWING ROUTINE FINDS THETA LOCATIONS WHICH ARE
C          LOCATED NEAR EACH OTHER.  THESE COLOCATED POINTS ARE
C          AVERAGED AND ASSIGNED THE NAME 'TAVG'.  THEN, THE TAVG
C          IS OUTPUT TO THE DATA FILE 'EXP WATFIV A1' FOR USE BY
C          THE DIAMETER FINDING PROGRAMS.  (TAVG IS ALSO OUTPUT TO
C          TO THE DATA FILE 'DIGITAL DATA')
C
         Z = M-1
         SUM = 0
         LL = 1
C
```

```
      DO 54 I=1, Z
      DIFF = ABS( THLOC(I+1) - THLOC(I) )
      IF(DIFF .LE. .005) THEN
      SUM = SUM + 1
      ELSE
      AVG(LL) = SUM + 1
      LL = LL + 1
      SUM = 0
      END IF
 54   CONTINUE
      AVG(LL) = SUM + 1
C
      MM = LL
      BB = 0
      DO 57 I=1, MM
      FF = AVG(I)
      AA = 0.0
      DO 56 II=1, FF
      AA = AA + THLOC(II + BB)
 56     CONTINUE
      BB = BB + FF
      TAVG(I) = AA / FF
 57   CONTINUE
C
C
      DO 61 I=1, MM
      IF(I.GT.3) GOTO 61
      WRITE(9, 60) TAVG(I), DESINT
 60   FORMAT(1X,E17.10, 1X,E17.10)
 61   CONTINUE
C
      WRITE(8 ,70)
 70   FORMAT(1X, 'THETA LOCATION', 4X,'DESIRED INTENSITY',/)
C
      DO 72 I=1, MM
      WRITE(8,71) TAVG(I), DESINT
 71   FORMAT(1X,E17.10, 1X,E17.10)
 72   CONTINUE
C
      WRITE(8, 73) M, Z, LL, MM, FF, SUM, DIFF
 73   FORMAT(1X, 'M = ', I2,/,1X,'Z = ',I2,/,1X,'LL = ',I2,/,1X,
     &'MM = ',I2,/,1X,'FF = ',I2,/,1X,'SUM = ',I2,/,1X,'DIFF = ',
     &F7.4,//)
C
      STOP
      END
C
C
```

```
C
C
C
C
C
C*****************************************************************
C          SUBROUTINE SLOPE
C*****************************************************************
C
C
C
C
      SUBROUTINE SLOPE(T, INT, K, GUDINT, NO, INTAVG, DIAMTR)
C
C     THIS SUBROUTING CALCULATES THE SLOPES OF A GIVEN INTENSITY
C     CURVE.  THE ROUTINE FINDS AND RETURNS THE VALUES OF THE MAXIMUM
C     DERIVATIVES, NAMED "GOODINT".  ALSO RETURNED IS THE AVERAGE OF
C     THE GOODINT VALUES, "INTAVG".
C
C     INT         =  VALUES OF INTENSITY RATIOS FROM CALLING PROGRAM
C       K         =  NUMBER OF VALUES PASSED FROM CALLING PROGRAM
C     GUDINT     =  VALUES OF THE MAXIMUM DERIVATIVES
C     NO          =  INTEGER NUMBER OF GOODINT VALUES
C     INTAVG      =  AVERAGE OF GOODINT VALUES ('DESIRED INTENSITY')
C
C
C
C
C
       INTEGER J, K, L, NO
       REAL T(400), INT(400), DER(400), DERIV(400), GUDINT(400)
       REAL INTAVG, A, DIAMTR
C
C
      CALL FRTCMS('FILEDEF ','11       ','DISK    ','DERIV   ','DATA    '
     *,'A1      ')
C
C
      L = K-1
C
      DO 25 I=1, L
      DER(I) = ( INT(I+1) - INT(I) ) / ( T(I+1) - T(I) )
      DERIV(I) = ABS( DER(I) )
   25 CONTINUE
C
      J = 1
      M = K-3
      DO 50 I=1, M
```

```
      IF((DERIV(I+1).GT.DERIV(I)).AND.(DERIV(I+1).GT.DERIV(I+2)))THEN
      GUDINT(J) = INT(I+1)
      J = J+1
      END IF
 50   CONTINUE
      NO = J-1
C
C
      A = 0.0
      DO 51 I=1, NO
      A = A + GUDINT(I)
 51   CONTINUE
      INTAVG = A / NO
C
C
C
C    SUBROUTINE SLOPE OUTPUT BLOCK. THIS SUBROUTINE PLACES OUTPUT
C     IN A FILE CALLED DERIV DATA ON THE USER A-DISK.  TYPE "PRINT
C     DERIV DATA" TO OBTAIN A PRINTOUT OF THE RESULTS FROM THIS
C     ROUTINE.
C
     IF(DIAMTR .NE. 0.0) THEN
     WRITE(11, 73) DIAMTR
 73  FORMAT(1X, 'FIBER DIAMETER = ',F7.4,'  MICRONS',/)
     ELSE
     WRITE(11,74)
 74  FORMAT(1X,'FIBER DIAMETER UNKNOWN',/)
     END IF
C
     WRITE(11,98)
98   FORMAT(3X, 'THETA',12X,'DERIVATIVE',/)
C
     DO 100 I=1, M
     WRITE(11, 99)  T(I), DERIV(I)
 99  FORMAT(1X,E17.10, 1X,E17.10)
 100 CONTINUE
C
     WRITE(11,150) INTAVG
 150  FORMAT(//,1X,'THE AVERAGE OPTIMUM INTENSITY IS: ',E17.10,//,
    &'AND THE INDIVIDUAL INTENSITIES ARE: ', //)
C
C
C
      DO 200 I=1, NO
      WRITE(11,199)  GUDINT(I)
 199  FORMAT(1X,E17.10)
 200  CONTINUE
C
```

```
      RETURN
      END
C*********************************************************************
C     END OF SUBROUTINE SLOPE
C*********************************************************************
C
C
C
C
C*********************************************************************
C           SUBROUTINE RANDOM
C*********************************************************************
      SUBROUTINE RANDOM(T, INT, INTERR, ERR, K, DIAMTR, IX)
C
C
C
C
C        THIS SUBROUTINE TAKES PERFECT DATA FROM THE CALLING PROGRAM
C        INTRODUCES RANDOM ERROR INTO THE DATA.  THE SUBROUTINE
C        RANDU IS USED TO CALCULATE RANDOM UNMBERS BETWEEN ZERO
C        AND ONE.  THESE NUMBERS ARE CHANGED TO BETWEEN -1 AND +1
C        GIVING EQUAL ERROR TO THE DATA (PLUS AND MINUS).
C        THE PROGRAM OUTPUTS THE DATA TO DATA FILES AS SHOWN IN THE
C        DEFINITIONS SHOWN BELOW.
C
C        VARIABLE DEFINITIONS:
C
C        INT    ARRAY OF PERFECT INTENSITY RATIOS
C        RAN    ARRAY OF RANDOM NUMBERS GENERATED BY RANDU
C          T    ARRAY OF THETA VALUES FROM PERFECT INTENSITY FILES
C     INTERR    ARRAY OF INTENSITY RATIOS WITH ERROR
C        ERR    VALUE OF INTRODUCED ERROR (E.G. 1% IS .01)
C          K    NUMBER OF INTENSITY RATIOS PASSED TO ROUTINE
C
C    IX,IY,YFL VARIABLES USED BY SUBROUTINE RANDU
C
C
      INTEGER IX, IY
      REAL INT(400), RAN(400), T(400), YFL
      REAL RANPM1(400)
      REAL INT1(400), INTERR(400)
      REAL MAXINT, THMAX, DIAMTR, ERR
C
C
C       SET UP THE DATA FILE; ........
C
      CALL FRTCMS('FILEDEF ','04      ','DISK    ','ERRDATA ','DATA    '
     *,'A1      ')
C
```

```
C
C       SEARCH INTENSITY RATIO FILE FOR THE MAXIMUM VALUE OF THE
C       INTENSITY RATIO.  NAME THIS VALUE 'MAXINT' AND ITS
C       CORRESPONDING THETA LOCATION 'THMAX'.
C
C
      M = K-1
      MAXINT = INT(1)
      THMAX  = T(1)
C
      DO 01 I=1, M
      IF( INT( I+1) .GT. MAXINT) THEN
      MAXINT = INT( I+1)
      THMAX  = T( I+1)
      END IF
 01   CONTINUE
C
C
C  CALCULATE THE RANDOM NUMBERS USING NONIMSL SUBROUTINE 'RANDU'
C
      DO 12 I=1, K
C
      CALL RANDU( IX, IY, YFL)
      IX = IY
      RAN( I ) = YFL
C
 12   CONTINUE
C
C
C       CHANGE THE RANDOM NUMBER RANGE FROM (0 TO +1) TO (-1 TO +1)
C
C
      DO 13 I=1,K
      IF( RAN( I ) .GT. .5) THEN
      RANPM1( I ) = 2 * ( RAN( I ) - .5)
      ELSE
      RANPM1( I ) = (-2) * ( RAN( I ))
      END IF
 13    CONTINUE
C
C
C         CALCULATE THE NEW INTENSITY ARRAY WITH THE INTRODUCED ERROR.
C         NOTE THAT ERROR IS BASED UPON MAXIMUM INTENSITY (WHICH WAS
C         FOUND ABOVE: 'MAXINT' AND 'THMAX')
C
      DO 15 I = 1, K
      INTERR( I ) = INT( I ) + (MAXINT * ERR * RANPM1( I ))
 15   CONTINUE
```

```
C
C
C         OUTPUT THE ARRAY ......
C
      IF(DIAMTR .NE. 0.0) THEN
      WRITE(4,73) DIAMTR
 73   FORMAT(1X,'FIBER DIAMETER = ', F7.4, '  MICRONS',/)
      ELSE
      WRITE(4,74)
 74   FORMAT(1X,'FIBER DIAMETER UNKNOWN',/)
      END IF
C
C
      WRITE(4,75) THMAX, MAXINT, ERR
 75   FORMAT(1X,'MAX INTENSITY RATIO OCCURS AT THETA = ', E17.10,/,
     &1X,'AND HAS MAGNITUDE = ', E17.10,//, 1X,'INPUT ERROR = ',
     &F5.3, //)
C
      WRITE(4,76)
 76   FORMAT(4X, 'THETA',11X,'INTENSITY', 9X,'INT. W/ERROR',//)
C
      DO 100 I=1,K
      WRITE(4, 99) T(I), INT(I), INTERR(I)
 99   FORMAT(1X,E17.10, 1X,E17.10, 1X,E17.10)
 100  CONTINUE
C
C
      RETURN
      END
C*********************************************************************
C      END OF SUBROUTINE RANDOM
C*********************************************************************
$ENTRY
```

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